THE INDUCTION VOLTAGE REGULATOR

THE INDUCTION VOLTAGE REGULATOR

Its Development, Design, Characteristics, Use, and Application

BY

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PREFACE

The induction voltage regulator has frequently been made the subject of articles appearing in bulletins, papers and reports. In some of these, various phases of feeder voltage regulation by means of induction regulators have been treated more or less fully. However, there has been a distinct need for a single authoritative publication devoted to a comprehensive discussion of the entire subject, and to that end much of the material previously published has been summarized and the essentials incorporated into a single text.

Issued at first in multigraphed loose-leaf form with illustrations made by the gelatin process, a limited edition was supplied only to those representatives of the General Electric Company who were especially interested in the induction regulator. Thus a complete treatise on the induction regulator was extant in the form of a series of co-related papers prepared and issued prior to December, 1920.

Because of the general interest taken in the subjects discussed, by the users of the class of apparatus described, and because of the increasing demand for copies of the publication, it was thought advisable to issue a printed edition which could more conveniently be given a wider distribution. The original text was therefore carefully revised, corrected, and brought up to date. In this work, as in the preparation of the loose-leaf form, an endeavor was made to present the induction regulator, together with its design, characteristics and uses, in as elementary a manner as permitted by the nature of the subject. All mathematical formulas were therefore omitted and the technical discussion was confined to a few simple and readily understandable vector diagrams and curves.

PREFACE

It is in this form that the author offers this text. In doing so, his aim has been not only to present a reliable treatise covering the induction voltage regulator and its auxiliary apparatus but also to demonstrate:

First. That, notwithstanding the difficulties which induction regulators sometimes present to the designer, they with their auxiliaries for automatic operation are exceedingly simple and from an operating standpoint require neither more technical knowledge nor care and attention than many other classes of electrical apparatus.

Second. That, although the automatic regulation of voltage has been viewed more or less as a refinement not absolutely essential to the operation of the central station and one which is of chief benefit to users of incandescent lighting, its real benefits accrue to the central station, particularly in the increase in the sale of energy, in the possibilities of reductions in the cost of line construction, in the ability to furnish uniform service, and in the economical interconnection of generating systems.

In conclusion, the author wishes to express his appreciation to those who have labored with him in the production of this volume. Especial credit is given to Mr. M. Unger for his assistance in the preparation of the sections dealing with the regulator and its auxiliaries, to Mr. F. Dubsky for assistance in the preparation of the sections dealing with generators and with the protection of the regulator, and also to other members of the department specializing in some of the subjects discussed.

E. F. G.

Pittsfield, Mass., April 6, 1922.

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PART I

FEEDER REGULATOR DEVELOPMENT, DESIGNS AND CHARACTERISTICS

SECTION I

INTRODUCTION

A close voltage control was demanded very early in the history of electric lighting because both the candle-power and the life of incandescent lamps were found to be sensitive to voltage changes. With the small direct-current generators first used, such control was accomplished by adjusting the generator field by means of a variable resistance. This adjustment was usually made by hand, and as long as each feeder was supplied by its own generator, this method of voltage control was fairly satisfactory. However, only two years after the introduction of the constant potential direct-current system, the advantage of automatic voltage control was recognized, and in 1882, an automatic generator voltage regulator was designed and used to some extent.

As the size of the generators increased and several circuits were supplied from a single station bus, new conditions were encountered. The voltage requirements of the individual feeders varied according to their respective loads (that is, according to the varying line drop), and as the individual feeders did not have a negligible voltage drop because of the low voltage used, the bus voltage was increased and an adjustable artificial loss in the form of a rheostat was inserted in each feeder. By means of these resistances, which constituted the first elementary feeder voltage regulators, the voltage of each feeder was adjusted in accordance with its requirements.

Due to the loss of power in the resistances, however, the cost of this method of feeder voltage regulation was found to be prohibitive. The resistances were therefore eliminated, the section of the copper in the feeder was

increased, auxiliary feeders were installed, and the various feeders were interconnected so as to obtain, as nearly as possible, a uniform potential drop on all feeders.

For the distribution of power over a small area, this latter arrangement was fairly satisfactory; but, with the extension of the feeder lines, it was found advisable to augment this equalization of voltage by voltage regulation obtained by means of series boosters and storage batteries.

The alternating-current system of distribution employing high-voltage generators and transformers passed through a similar cycle of development. The first generators were of small capacity and attempts at multiple operation were generally unsuccessful. Accordingly, the practice for several years was to operate a single feeder from each generator, and to obtain feeder voltage control by regulating the field of the generator.

The development of larger alternating-current generators and improvements in their design (as well as in the design of the governors of their prime movers, so as to permit multiple operation) again resulted in the operation of several feeders from the same generator or station bus, and the individual voltage control of each feeder was found to be just as necessary as had previously been experienced in direct-current distribution. The difficulties experienced in the voltage control of direct-current feeders were not encountered, however, for apparatus which is both reasonable in cost and economical in operation can readily be designed for the control of the voltage of alternating current.

A variable reactance or choke coil connected in series with the feeder constitutes one of the simplest forms of such apparatus, and it was used to some extent. As with the resistance method, this device also necessitates an

increase in the bus voltage and depends for its regulation upon the amount of current flowing. Its voltage range must therefore be large because a maximum lowering of the voltage is required when the current is smallest. Moreover, the voltage drop across the series reactance is out of phase with the voltage of a high power-factor circuit. This again necessitates an increase in its voltage range so that the kv-a. capacity of the reactance becomes extremely large compared with the results obtainable. These objectionable features make the reactance unsatisfactory for voltage control. The transformer, or rather compensator, regulator was therefore developed, and in one of its forms is the present standard.

The first design of this type of regulator, known as the switch type, consisted of a transformer core with primary and secondary windings. The primary winding was connected across the line to be regulated and the secondary was connected in series with the line. The series winding was, however, divided into sections. By means of a switch, any number of these sections could be cut in or out of circuit and the winding could be reversed. With this arrangement, any one of a number of voltages can therefore be added to or subtracted from the line or bus voltage depending upon the number of secondary winding sections included in the feeder circuit and the direction of the voltage in this winding with respect to the line voltage. This type of regulator is still used to some extent; but, due to difficulties in switching, a number of other designs of regulators were devised. In these, the entire secondary or series winding is left permanently connected in series with the line and the change in the amount and direction of the regulator voltage is obtained by changing the number

or the direction of the magnetic lines, produced by the primary or exciting winding, through the series winding.

One design, used to a limited extent, consisted of an open magnetic circuit core with the primary wound directly upon it, and an adjustable series winding which could be moved from a position over the center of the primary to one entirely out of the path of the flux. This movement of the secondary varied its induced voltage from its maximum to zero. The voltage was also reversible, its reversal requiring the reversing of this coil or its connection.

In another design which was extensively used, the sheet iron core consisted in part of built-up circular punchings. A primary and a secondary coil were assembled in four slots on the inside circumference of this core and at right angles to each other. Forming part of the core and the magnetic circuit was a built-up sheet iron shuttle rotatable within the circular core and coils through a sufficient angle to change the direction of the magnetic flux through the series winding; the direction of the flux through the primary winding, however, remaining unchanged.

When the shuttle was midway between the series and shunt winding, the maximum voltage was obtained; when it spanned the series coil only, the induced voltage in this coil was zero. When the shuttle was rotated in the same direction so as again to be midway between the coils, the maximum voltage was again obtained but its direction was reversed. This design of regulator was designated and known as the MR type.

The modern design of regulator, in general use since 1904, is similar to this MR design, except that only the series winding is assembled in the stationary core while the primary, or exciting winding, is assembled on the

shuttle or rotating core. This type is designated as the IR or "Induction Regulator" and is the subject of patent No. 542,968 issued to C. P. Steinmetz and A. H. Armstrong in 1895, and patent No. 571,467 issued to A. H. Armstrong in 1896. These patents cover the single-phase and the polyphase designs respectively. In this design of regulator, the arrangement of the cores and coils is adaptable to either single-phase or polyphase construction.

The voltage regulation obtainable is independent of the feeder current. The regulator is substantial in construction and economical in operation, and therefore meets practically all feeder voltage regulator requirements.

The foregoing brief outline of the development in voltage regulation apparatus indicates that the need of feeder voltage regulation was recognized at almost the very beginning of the electrical industry. With the development of the industry, this subject has required and has been given much thought and study. The economies obtained by central stations and the benefits derived by their customers as a result of the proper use of voltage regulators are generally recognized, and in the near future, the public service commissions of all states will undoubtedly prescribe and demand (as some have already done) the proper regulation of the voltage of electrical energy supplied by all public service corporations.

A general presentation of the theory, design, construction and operation of the induction regulator and of the various auxiliaries used with it should therefore be of interest to those who use this class of apparatus.

SECTION II

GENERAL PRINCIPLES OF THE INDUCTION REGULATOR

In effect, the induction regulator is a variable-ratio transformer, or rather auto-transformer, having two separate and distinct windings; namely, a primary and a secondary. The primary winding is connected across the feeder to be controlled, while the secondary winding is

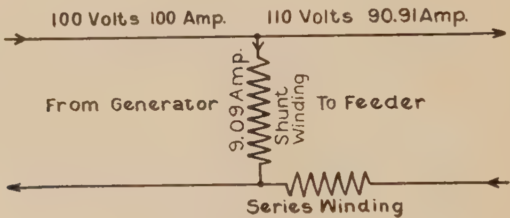


Fig. 1
Regulator Boosting

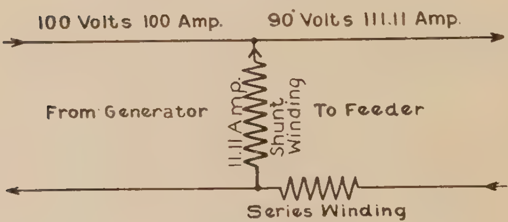


Fig. 2
Regulator Lowering

connected in series with the feeder. The product of the volts and amperes on the generator or busbar side, less the small loss in the regulator itself, is always equal to the product of the volts and amperes on the feeder side.

This applies to both single-phase and polyphase regulators and may be illustrated as in Figs. 1 and 2 which

show respectively the conditions existing in a 10 per cent auto-transformer connected in a 100-volt, 100-amp. circuit when boosting and when lowering the feeder voltage. Disregarding the small loss in the auto-transformer, the values of the currents and voltages will be as given in these diagrams.

As the induction regulator is in effect an auto-transformer and is identically connected, as shown in Figs. 1 and 2, the same conditions apply not only in the maximum boosting and lowering positions of the regulator but also in intermediate positions, as will be shown hereinafter.

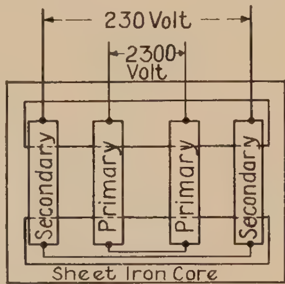


Fig. 3
Elementary Transformer Diagram

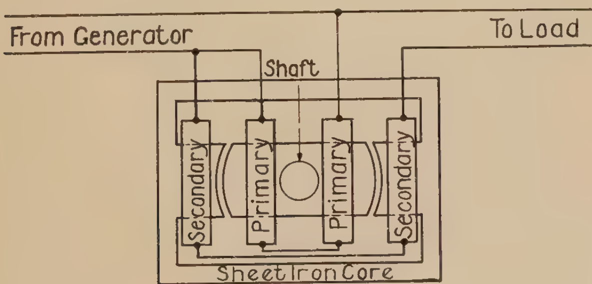


Fig. 4
Elementary Regulator Diagram

In a regulator capable of producing a total voltage variation of 20 per cent as illustrated, and with this regulator in the maximum boosting position as shown in Fig. 1, about 9 per cent of the current from the generator flows through the primary winding of the regulator and back

to the generator. This amount is therefore deducted from the current in the feeder, but the feeder potential is thereby increased 10 per cent. With the regulator in the maximum lowering position, the current in its primary winding is reversed. This increases the feeder current by 11 per cent, as a result of lowering the voltage by 10 per cent.

The analogy between the induction regulator and a transformer may be further illustrated by diagrams (Figs. 3 and 4). One of the standard arrangements of the primary and secondary windings and the core in transformer construction is shown in Fig. 3. The construction shown in Fig. 4 is identical except that, in this case, the center leg of the core is cut as shown, and mounted on a shaft.

As modified, that part of the core mounted on a shaft, and on which the primary coils are assembled, is designated as the primary core, rotor, or armature. The stationary or fixed part of the core containing the secondary windings is designated as the secondary core or stator.

In a standard transformer, both the value and the direction of the voltage induced in the secondary windings are definite and fixed with respect to the value and direction of the voltage applied to its primary winding. With the modified construction shown in Fig. 4, however, it is variable because of the possibility of changing, not only the percentage of the magnetic flux produced by the primary through the secondary, but also its direction. In the position shown in Fig. 4, all the primary flux passes through the secondary coils, and the voltage induced in the secondary winding is equal to the primary or line voltage divided by the ratio of primary turns to secondary turns. As the primary core is rotated, the amount of primary flux passing through the secondary winding is decreased until the core reaches a position at right angles

to that shown. In this position, no primary flux passes through the secondary coils and the induced voltage in this winding is, therefore, zero. The continued rotation of the core in the same direction again increases the amount of the flux threading through the secondary, but it is now in the opposite direction and so reverses the direction of the voltage induced. By connecting the secondary winding in series with a feeder and the primary winding across the line, as shown in Fig. 4, the feeder voltage can therefore be varied by adding to or subtracting from it the voltage induced in the secondary winding.

In the actual design of the induction regulator, the arrangement of cores and coils is a modification of that shown in Fig. 4. Both the primary and the secondary cores are circular, and the coils are assembled in recesses or slots, similar to those of an induction motor. With this modification, the changing of the amount and direction of the primary flux which threads through the secondary winding is more gradual than obtained with the elementary design shown in Fig. 4 and a more uniform voltage change is obtained. Furthermore, this modification makes it possible to assemble a polyphase winding on a single core.

For both the single-phase and polyphase arrangements, the windings on both the rotor and stator cores are, in effect, polar windings. The means by which the voltage variation on the line is obtained by the use of the single-phase and the polyphase regulator, however, is somewhat different, and therefore, each design will be discussed separately.

SECTION III
THE SINGLE-PHASE REGULATOR

The arrangement of the rotor and stator cores and windings of a single-phase regulator is shown diagrammatically in Fig. 5. The excitation of the cores is single-phase. Thus the magnetizing flux is an alternating one and

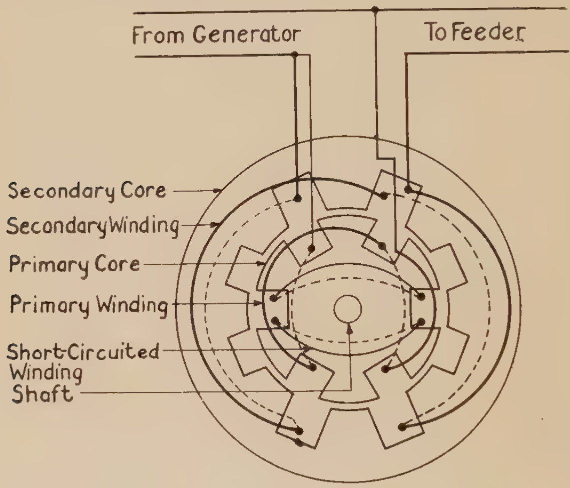


Fig. 5
Arrangement of Primary (Armature) and Secondary (Field) Cores and Winding of a Single-Phase Induction Voltage Regulator
(Armature in Maximum Lowering Position)

always threads or passes through the entire primary or exciting winding, and its direction is always parallel to that diameter of the movable core which passes through the center of the exciting coils. The direction of this flux may, however, be varied with respect to the stationary core and, consequently, with respect to the stationary or series winding (the secondary winding).

As the primary core is rotated, thereby changing the relative direction of this flux, the amount threading the

secondary coils is varied. This produces, in the secondary winding, a voltage which gradually varies from the maximum positive, through zero, to the maximum negative value. The induced voltage is, however, always in phase with the excitation voltage and is therefore added directly to or subtracted directly from the line voltage.

The Short-Circuited Winding

The primary or rotating core contains two windings: the active or shunt winding, connected across the line; and a second winding, short-circuited on itself and arranged at right angles to the shunt winding as illustrated in Fig. 5. The object of this short-circuited winding is to equalize the losses and the reactance of the regulator in its various positions of boost and lower. Its operation is as follows:

As the primary and short-circuited windings are both on the movable core and permanently fixed at right angles to each other, the magnetization produced by the primary passes equally on both sides of the short-circuited coil. As long as no magnetic lines pass through this coil, no current flows in it. However, this condition holds only when the rotor is in the maximum boost or maximum lower position with current flowing in the series winding, or when the rotor is in any position with no current in the secondary.

With the rotor in either the maximum boost or maximum lower position, practically all of the magnetic flux passes through both primary and secondary coils. The line current flowing through the series winding causes a corresponding current to flow in opposite direction through the shunt or primary winding. The currents themselves are not necessarily identical, but the product of the current and the number of turns (i.e., the ampere-turns) in one winding is equal to the ampere-turns in the other winding. With

the rotor in either the maximum boost or maximum lower position, no current flows in the short-circuited winding.

With the rotor in the neutral, or no boost and no lower position, the magnetization produced by the ampere-turns of the secondary passes equally on both sides of the primary coils. That is, when the rotor is in the neutral position, the primary and secondary windings are no longer in an inductive relation to each other. In this position, the primary winding carries the normal magnetizing current only. It carries no load current regardless of how much load current flows in the secondary or series winding. The short-circuited winding on the primary core and at right angles to the primary or shunt winding is, however, now in an inductive position to the series winding. As the short-circuited winding on the rotor is short-circuited upon itself, it in effect short circuits the series winding when the rotor is in neutral position. Thus it allows the line current to flow through the series winding with practically no voltage drop or change in the line voltage. With the rotor in this position, the maximum current flows in the short-circuited winding and its ampere-turns are equal to the ampere-turns of the series winding.

If the primary core were not provided with the short-circuited winding and were rotated from either maximum position so as to reduce the primary flux passing through the secondary winding, and if the line current remained constant, a gradually increasing voltage would be required to force the line current through the series winding and a correspondingly increased flux would be induced by this winding, thereby increasing the loss. This voltage would reach its maximum value when the armature is in the neutral position as in this position the shunt winding is at right angles to the series winding, and therefore is entirely

out of inductive relation to it. The series winding would then operate as a reactance and an appreciable percentage of the line voltage would be required to force the line current through the series coils. The voltage so used would

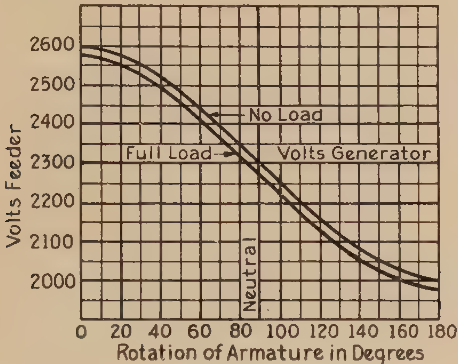


Fig. 6
Curves Showing Boosting and Lowering of Feeder Voltage by an Induction Regulator

be at right angles to the line voltage, but it would result in a lowering of the line voltage and in a reduction of the power-factor. However, the short-circuited coil on the rotor, which is—as already stated—in direct inductive relation to the stator winding when the rotor is in the neutral position, acts as a short circuit on the stator winding and greatly reduces the voltage necessary to force the line current through this winding.

This short-circuiting of the series winding is gradual and extends from a zero value in the maximum boost position of the regulator to the maximum short-circuiting in the neutral position. Thus, by the combined effects of the shunt and short-circuited coils, the reactance of the series winding is kept within reasonable limits, and, consequently, produces no appreciable effect on the line. This

can be seen by referring to the full-load and no-load boost and lower curves (Fig. 6) which have been plotted from actual tests and not from merely theoretical calculations.

The operation of the short-circuited coil does not increase the losses in the regulator, but rather tends to

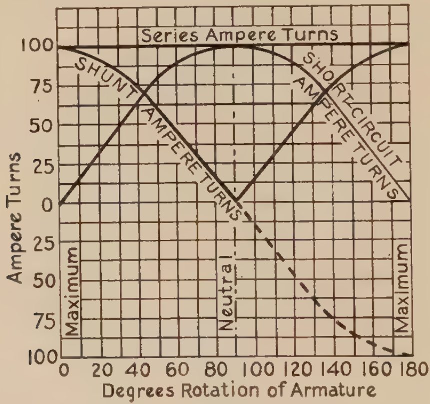


Fig. 7
Current Relations in an Induction Regulator

keep them constant for any given line current. In rotating the armature from either maximum to the neutral position, the current in the primary diminishes as the current in the short-circuited coil increases. This is illustrated in Fig. 7, in which the curves are plotted to show ampere-turns instead of current. With a constant current in the series winding represented by 100 ampere-turns, and with the regulator in the maximum boosting position, there is a corresponding number of ampere-turns represented by the shunt winding and zero ampere-turns represented by short-circuited winding. As the armature is rotated toward the neutral position, the ampere-turns of the primary decrease and those of the short-circuited winding

increase until at the neutral position they are zero for the primary and 100 for the short-circuited winding. The continued rotation of the armature again increases the ampere-turns of the primary and decreases those of the short-circuited winding as shown.

Theoretically, the primary current passes through zero value, and with reference to the line current, it reverses in direction as indicated by the dotted curve in the lower half of the diagram. By actual test it is impossible to obtain zero current in the primary because of the magnetizing current which is not taken into consideration in the curves. However, the reversal of current in the primary can be noted by comparing this current with the line current on both sides of the regulator, as illustrated in Figs. 1 and 2. It will be observed that the currents in the two windings on the rotor do not increase and decrease at the same rate as the armature is rotated but that they vary as a sine curve. The arithmetical sum of the ampere-turns on the rotor will therefore vary for different positions of the armature. This value will be a maximum when the rotor coils are at an angle of 45 degrees to the stator coils, in which position the ampere-turns of each rotor coil are equal to 71 per cent of the ampere-turns of the stator. The currents in both rotor windings are in phase, but due to the mechanical displacement of the coils, the effective counterbalancing ampere-turns of these two windings are not their arithmetical sum, but their vectorial sum.

If all three windings were identical and the current in the series winding 100 per cent, then, at the 45-degree position of the rotor, the current in each winding on the rotor would be 71 per cent. Hence, the I^2R loss would be 71^2 times the resistance times 2. This is equal to 100^2 times

the resistance; that is, excluding the magnetizing current, the copper loss is constant throughout the range of control.

The effect of the angular displacement of the rotor coils with respect to the stator winding is, however, noticeable in the impedance as illustrated in Fig. 8 which gives

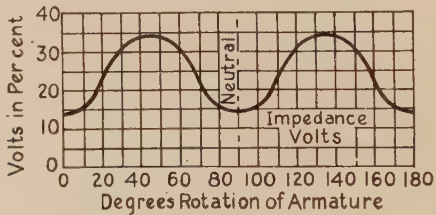


Fig. 8
Impedance Curve of an Induction Regulator

the impedance volts across the series winding in per cent of the maximum voltage induced in this winding. For all positions of the armature except either maximum and neutral, both rotor coils are out of direct inductive relation to the stator coil. The ampere-turns of the rotor are therefore not so effective in reducing the voltage required to force current through the series windings. This voltage attains its maximum value when the armature is halfway between either maximum and the neutral position, or in other words, when the rotor coils are displaced by an angle of 45 degrees with reference to the stator coil. Currents flowing through the windings, when in this position, produce a maximum distortion of the magnetic flux which flux distortion tends to cause the armature to vibrate more in this position than in any other. This instability is more noticeable in regulators of the older designs, but has been compensated for in regulators of modern design.

SECTION IV
THE POLYPHASE REGULATOR

The arrangement of the primary and secondary cores and windings of a three-phase regulator is shown diagrammatically in Fig. 9. All polyphase regulators are similarly

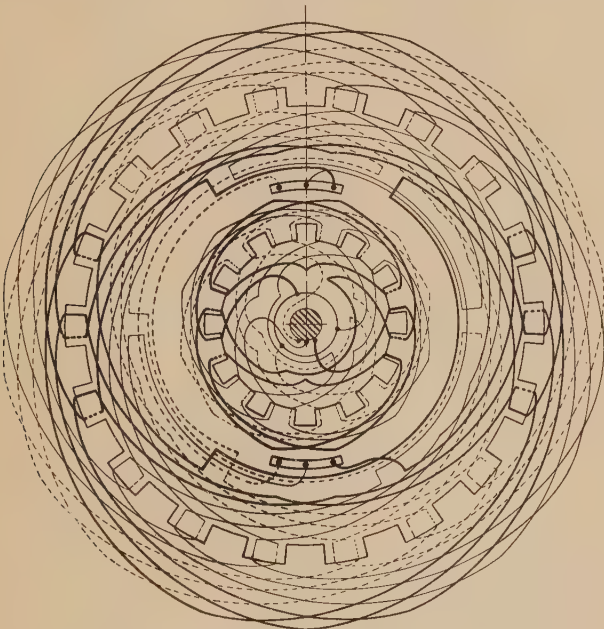
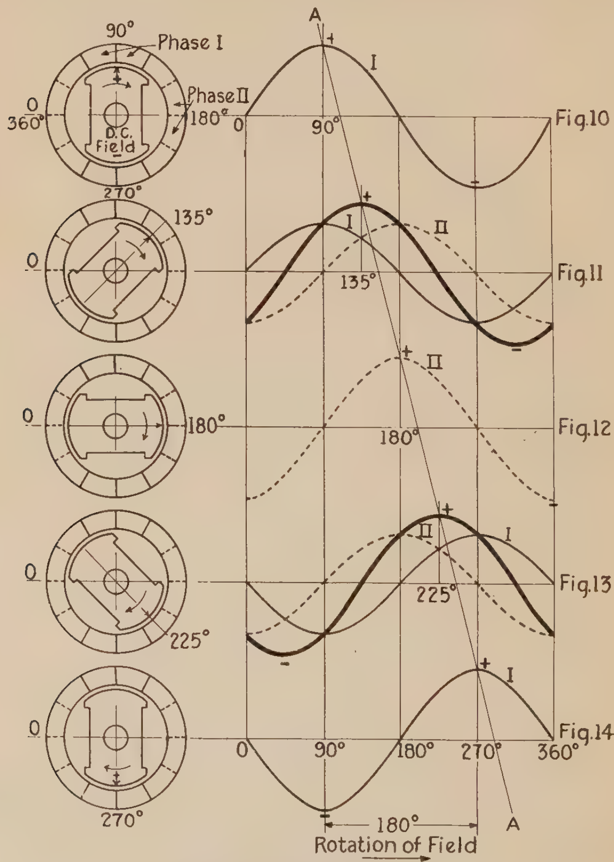


Fig. 9
Wiring Diagram of Three-Phase Regulator

arranged; that is, every polyphase regulator has one shunt winding and one series winding for each phase. As in the single-phase design, the shunt (or primary) windings are connected across and the corresponding series (or secondary) windings in series with the line to be regulated. The current in each winding is single-phase, but the magnetization of the core is produced by the combined action of all

the shunt windings. These windings are identical, and are so arranged and connected that all of the shunt windings



Figs. 10 to 14
Diagram of A-C. Field Rotation

embracing any pole magnetize that pole in the same direction. That is, the windings are arranged and con-

nected to the line in the same order as similar windings on the generator. The magnetization produced by any individual phase winding would be an alternating one; but, as each pole of a polyphase regulator is excited by each of the phases of the line, and as the windings are distributed along the poles in the same manner as those of the generator, they are excited successively in the same order and at the same rate of speed as the voltage is produced in the generator windings by the rotation of the generator field. This succession of the individual phase excitation produces in the regulator core a magnetization which has a constant value but which rotates at the same angular speed as the generator armature from which the excitation is obtained.

Rotation of Field

The rotation of the field is illustrated in Figs. 10 to 14 inclusive. These illustrations show, diagrammatically, a two-pole two-phase generator winding with its direct-current excited armature and the revolving magnetic field due to the rotation of the armature.

The curves designated by + and – represent the magnetic field with a sine wave distribution of the flux over the pole face. This field, produced by the direct-current excitation of the armature, rotates with the armature and produces a sine-shaped voltage in each of the stator windings, curves I and II.

The same kind of rotating field can be produced by applying polyphase alternating current to the stator, in the present instance, two-phase excitation.

A stationary field (as shown in Fig. 10) can be obtained by applying continuous current to the winding of phase II of the stator; a field such as shown in Fig. 12 can be obtained by applying continuous current to phase I of the stator.

It also is evident that a field such as shown in Fig. 11 can be obtained by applying, to both phases of the stator, excitations which are equal to each other but of less value than before.

A forward movement or rotation of the field can therefore be produced by applying a continuous-current excitation to phase II and zero excitation to phase I, then gradually diminishing the excitation of phase II and increasing the excitation of phase I until the former is zero and the latter is equal to the initial excitation of phase II.

A further rotation of this field can be obtained (as in Figs. 13 and 14) by reversing the direction of the excitation in phase II and gradually increasing it while correspondingly decreasing the excitation of phase I. The entire cycle or revolution of the field can thus be obtained by successive variations and reversals of the continuous-current excitation.

The variations in the value and direction of the continuous current, as described, correspond to the alternating-current voltage induced in the stator windings by the rotation of the direct-current excited armature. Hence, they also correspond to the currents obtainable from these windings under normal operating conditions. The windings of the regulator duplicate those of the generator in their arrangement, and the shunt or exciting windings of the regulator are connected directly to the generator windings. For the successive positions shown in Figs. 10 to 14, the voltages induced in phases I and II of the generator successively excite the corresponding regulator windings, and the magnetizing currents in the windings on the regulator core vary in value and direction in a manner similar to the voltages of the generator.

In the two-phase winding under consideration, the current in phase I of the regulator is a maximum when the

current in phase II is zero. The current in phase I decreases while that in phase II increases until the value of the former reaches zero. At this point, the current in phase I reverses in direction. Simultaneously, the current in phase II begins to decrease, and so on through the cycle. The variations are identical with those described to show how a rotating field can be obtained in the generator windings by applying continuous current to these windings. The alternating-current excitation of the shunt windings of the regulator therefore produces in the regulator core a rotating field identical to that produced by the mechanical rotation of a direct-current field. Thus, the secondary or series winding of the regulator may be considered as constituting the alternating-current winding of a second generator connected in series with the main generator and operating in synchronism with it.

It will be observed from the foregoing that, although each phase excitation produces an alternating field as in a transformer, a rotation of this field is produced in the regulator core by the successive excitation of the overlapping single-phase windings.

The change in the position of the maximum magnetization of the regulator core is gradual and uniform, and is made at a speed having the same rate as that of the armature of the generator from which the excitation of the regulator is obtained. The magnetization is also practically constant but depends not only on the summation of the voltages of the various phases producing the excitation but also on the number and arrangement of the slots of the core containing the winding.

In the previous section was shown how the voltage across the series winding of a single-phase induction regulator is varied in value by varying the amount of the

magnetic flux passing through this winding. This variation is obtained by varying the angular position of the rotor with respect to the stator.

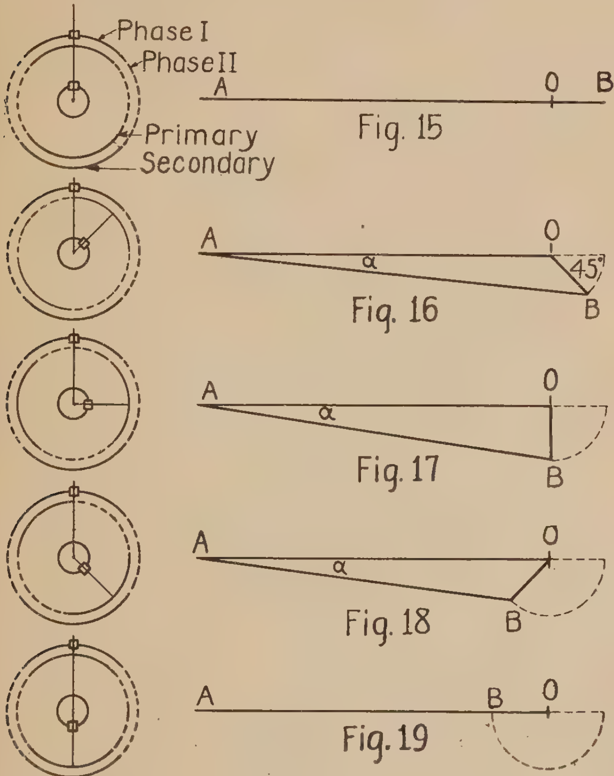
It also has just been shown that, in the polyphase regulator, the flux passing through the series winding has a constant value regardless of the relative position of rotor to stator but that it rotates at a speed corresponding to the frequency of the circuit. That is to say, the frequency of the voltage alternation in the single-phase regulator corresponds to the speed of the rotating field in the polyphase design and, hence, to the frequency of its voltage alternations.

The rotation of the field or magnetization in the core of a polyphase regulator therefore produces a voltage of constant value in each secondary or series winding regardless of the relative angular positions of these windings to each other, and the change in the line voltage is produced by a phase displacement of the induced voltage and not by a change in the magnitude of this voltage as in the single-phase design. This is illustrated in Figs. 15 to 19, inclusive, which represent diagrammatically: the shunt and series windings of a polyphase regulator; the voltages impressed; the voltages induced; and the resultant line voltage.

Induced or Secondary Voltage

In Fig. 15, phases I and II of the primary are directly opposite to, and enclose the same pole area as, the corresponding phase windings of the secondary. In this position of primary and secondary, each phase may be considered as an entirely independent single-phase circuit, each secondary or series winding producing its maximum boosting effect on the line in exactly the same manner as the series winding of a single-phase regulator. This is illustrated in the voltage diagram, where *AO* represents the

generator voltage and OB represents the voltage induced in the series winding of the regulator. With the primaries and secondaries in the positions shown, the secondary



Figs. 15 to 19
Diagrams of Voltage and Current Rotation in a Polyphase Induction Regulator

voltages are in phase with the generator voltages and add directly thereto; the resultant line voltages are AB.

In rotating the armature through an angle of 45 degrees, the induced voltage in each series winding is due

to the combined action of both of the phase windings of the armature. This combined effect of the armature windings is shown in Fig. 11. It is equal to the summation of the reduced effects produced by each individual phase when each is displaced through an angle of 45 degrees.

The voltage induced in the series winding is of the same magnitude as before but, as shown in Fig. 16, is out of phase with the generator voltage by 45 degrees. Although the resultant line voltage is still AB, it is not only less than shown in Fig. 15 but it has also been displaced through the angle α; that is, the generator voltage is AO, the line voltage is AB, and they are out of phase by the angle α.

On continuing the rotation of the regulator armature to the position shown in Fig. 17, phase I of the primary is in direct inductive relation to phase II of the secondary and phase II of the primary is in direct inductive relation to phase I of the secondary. Each secondary is affected by one primary only. The voltage induced in phase II of the secondary will be in phase with the voltage of phase I of the generator; but, as phase II of the regulator is in series with phase II of the generator and as the voltages of phases I and II are at right angles to each other, the voltage induced in phase II will be added to the line at an angle of 90 degrees as shown. The resulting line voltage is again AB but it is of less value than before and is more out of phase with the generator than previously.

A further rotation of the primary decreases the line voltage and also diminishes the phase displacement, as shown in Figs. 18 and 19. Fig. 19 shows the position of maximum lowering or minimum line voltage with the induced voltage of the regulator again in phase with the generator voltage. From the foregoing, it will be observed that the secondary voltage of a polyphase regulator is

constant regardless of the position of the armature and that the voltage regulation of the line is obtained by changing the phase relation of the regulator voltage to the generator voltage. It also will be noted that the line voltage is out of phase with the generator voltage except with the regulator in its maximum boosting or maximum lowering position.

This analysis of the secondary voltage of a polyphase regulator applies equally well to the analysis of the currents in the shunt windings. As previously indicated, if rotor and stator coils are in an inductive relation to each other, the ampere-turns of the rotor (and exclusive of the magnetizing or exciting current) equal the ampere-turns of the stator. In other words, the ratio of the current in the rotor coils to the current in the stator coils corresponds to the ratio of the number of turns in the stator coils to the number of turns in the rotor coils. This relation of the current in the primary windings to the current in the secondary windings of a polyphase regulator applies to all coils which are in an inductive position to each other regardless of the phases to which the coils may be individually connected.

The current in any primary winding always flows in an opposite direction to the current in the secondary winding in inductive relation thereto, and is designated as the ratio current. The total current in the primary is, however, composed of two components: the magnetizing current, which is always at right angles to the generator voltage; and the ratio current. The magnetizing current is due to the voltage across the shunt windings and it determines the voltage across the series windings. The load current in the series windings, however, determines the ratio current in the shunt windings in value and in direction.

Rotation of Primary Current

From the preceding, it is evident that as the position of the rotor is changed with reference to that of the stator the ratio currents in the shunt windings are shifted in phase.

Figs. 15 to 19 may be considered as current diagrams in which: *OA* represents the load current, that is, the current in the series winding of the regulator; *OB* represents the ratio current in the shunt winding of the regulator; and *AB* represents the current from the generator. In Fig. 15, the rotor current *OB* is in phase with the load current *AO*. In Fig. 16, phase I of the rotor is in inductive relation to both phases I and II of the stator. Thus, the position of the rotor or ratio current must be midway between phases I and II (or at an angle of 45 degrees to the load current) and so on until, in Fig. 19, the ratio current is again in phase but is in the opposite direction.

It will thus be observed that, with a constant load current flowing through the series windings of a polyphase regulator, the ratio current in the primary windings is also constant regardless of the position of the rotor with respect to the stator and also that this current shifts in its phase relation to the generator current with the rotation of the regulator armature, and is added to or deducted therefrom as in the single-phase arrangement.

In Fig. 15, illustrating the position of maximum boost, the current *AO* in the feeder is less than current *AB* delivered by the generator. The former is, however, at a higher voltage. In Fig. 19, illustrating the position of maximum lower, the current *AO* in the feeder is greater than the current *AB* delivered by the generator but it is at a lower voltage, and so on for all intermediate positions.

Neglecting the exciting current, with the single-phase connection, the current supplied by a generator to a

feeder is always the arithmetical sum of, or the difference between, the current in the regulated feeder and the current in the shunt winding of the regulator, whereas with the polyphase connection, it is the vectorial sum.

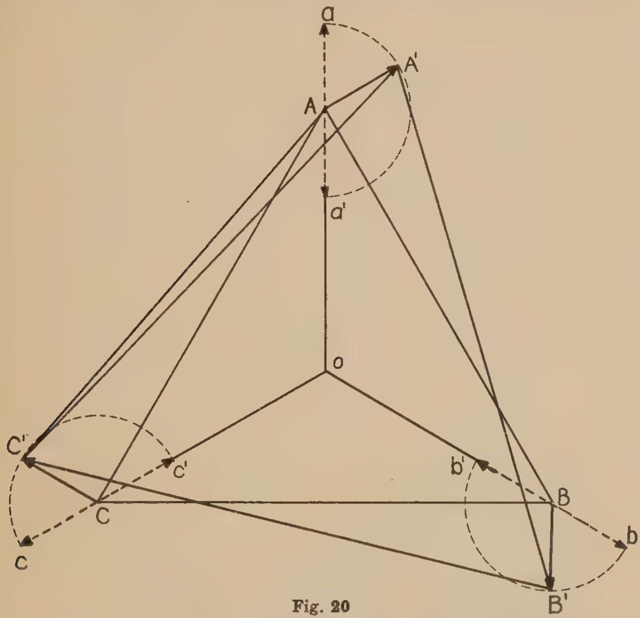


Fig. 20
Voltage Diagram of a Three-Phase Regulator

As all series windings of a polyphase regulator always have shunt windings in an inductive position regardless of the position of the armature, the short-circuited winding, so essential in the single-phase regulator, is not required. This results from the fact that the other phase windings act as short-circuited windings in the manner just illustrated. The same uniform voltage curves (Fig. 6), therefore, also represent the results obtainable with any polyphase regulator.

The impedance voltage curve of each phase of a polyphase regulator has the same general characteristic as shown in Fig. 8.

The operation of the three-phase design is identical with that of the two-phase and it can be similarly illustrated. The two-phase design has been used for illustration only because of the greater simplicity of its diagrams.

Regulated Voltage

Fig. 20 shows the complete voltage diagram for a three-phase regulator in which the phase voltages of the primary are OA, OB and OC. The primary voltages of the regulator with a Y-connected exciting winding correspond to the phase voltages of the bus or line from which the regulator is excited. The corresponding voltages induced in the series windings are Aa, Bb and Cc. These voltages, however, rotate about the points A, B and C respectively, depending upon the position of the regulator rotor with reference to its stator. In conjunction with the bus voltages they produce the resulting feeder voltages $A'B'C'$. As will be seen from the diagram, the regulation of the voltage across each phase of the feeder is produced by the combined action of the induced voltages of two phases of the regulator. In other words, the feeder voltage $A'B'$ is the resultant of the bus voltage AB and the two regulator voltages AA' and BB', and so on. It also will be noted that only when the regulator is in the maximum boosting or maximum lowering position is the induced voltage in the secondary of the regulator in phase with the phase voltage of the bus. Stated otherwise, the regulated feeder voltage $A'B'C'$ is out of phase with the generator or bus voltage ABC except in these two positions of the regulator.

The complete voltage diagram of a two-phase system can be similarly drawn and will show similar results.

SECTION V
ELECTRICAL DESIGN

The electrical design of the induction regulator is similar to that of an induction motor having a definitely wound armature. The same methods of calculation and the same formulas are used for predetermining its performance. The induction regulator, however, differs from the induction motor in the following particulars. The ratio of its primary turns to secondary turns is fixed by the voltage regulation required. Both the primary and the secondary windings must be insulated for the line potential. As the secondary of the regulator is connected in series with the line and is therefore subjected to line disturbances, extra insulation must be provided between turns and layers. Since both windings are stationary, they must be more liberally designed to keep the temperature within prescribed limits.

Slot Ratio

The number of winding slots in the rotor and stator must be such as to prevent magnetic locking.

As both of the regulator windings are in effect polar windings, and since all poles as well as all phase windings on each core must be identical, the requirement regarding ratio of slots demands that the number of slots per pole per phase be odd. If the armature is provided with two slots per pole per phase, the field may be provided with any other number which is not a multiple of two, and so on.

Windings

From statements already made, it is evident that the windings of a regulator must be designed so as to satisfy the following requirements:

First. The ratio of primary turns to secondary turns as determined by the voltage regulation requirements.

SECOND. The ratio of winding slots in the primary to those in the secondary, as determined by the requirement of a uniform flux density in the air gap for all positions of the armature so as to prevent magnetic locking. (The choice of this ratio is, however, limited by the number of phases of the circuit for which the regulator is required, and also by the number of poles for which the regulator is designed.)

THIRD. The windings for all phases on the rotor must be identical both with respect to the number of turns and number of coils. The windings on the stator must satisfy the same condition.

FOURTH. For economy, the conductors in the slots of both rotor and stator should be symmetrically arranged.

Coil Insulation

Due to the requirement that regulators be wound for the voltage of the distributing system with which they are to be used, and due to the relatively small kv-a. capacity of the regulator, copper of small section is required for the shunt winding. The insulation on the outside of the coils, that around the individual conductors, and that between layers may therefore occupy a considerable proportion of the space in the slots of the core. In the case of a small 2300-volt polyphase regulator, the ratio of copper to insulation is about 1 to 4. The greater part of this insulation is on the outside of the coil, and for this reason the number of slots is always reduced to a minimum. This, too, is one of the reasons for winding regulators two-pole; the minimum number of slots for a two-pole, three-phase machine is 12, whereas a four-pole regulator requires 24. The number of turns which can be insulated together and assembled in a single slot is, however, limited by: the relation between the width of slot and width of tooth

(because of magnetic locking); the reactance of the windings (which is proportional to the square of the number of turns in the slot times the number of slots in series); and the heating (because the cross section of the coil increases much more rapidly than its periphery). Small regulators are therefore wound two-pole with two slots per pole and phase on the rotor. Regulators of medium size are also of the two-pole design but they have a greater number of slots per pole and phase. Large regulators are of the four-pole design, and as in the two-pole arrangement, the number of slots used increases as the kv-a. capacity increases.

Magnetizing Current

For a given line voltage and frequency, the total number of magnetic lines which thread the coils varies inversely with the number of turns in the coils, whereas the magnetic flux density in the various parts of the magnetic circuit depends upon the cross section of the magnetic path.

With a given line voltage and frequency the magnetizing current then depends upon the various flux densities, upon the lengths of the magnetic circuits and upon the number of turns in the exciting winding. Since a low magnetizing current, as well as a small number of turns in the windings, are both advantageous, the sections of the magnetic path are made as large, and their lengths as short, as possible. With this in view, regulator coils are usually wound with 100 per cent pitch (that is, the coils span 180 electrical degrees of the core) and the cores are made with as small a diameter as practicable. As the greater part of the magnetizing current is used in the air gap between rotor and stator, the use of a two-pole winding is advan-

tageous for the reason that, for a given number of turns on a given core, the area of the air gap for a two-pole winding is twice (and hence the flux density is one-half) that for a four-pole winding, whereas the flux density in the core is the same with either winding arrangement. As, however, the reactance is reduced by increasing the air gap, which reduction is also desirable, the section of the air gap is made as large as possible in order to reduce the flux density, and the length is made as great as possible without permitting the magnetizing current to increase beyond reasonable limits.

Regulator Losses

In the design of any regulator, except one which is to be operated at full load continuously, a low iron loss is of greater importance than a low copper loss. This is due to the fact that the iron loss is constant for 24 hours a day, whereas the copper loss varies as the square of the line current. The iron or core loss increases or decreases as a function of the flux density in the core, and directly as the weight of the core and, from a design viewpoint. must be limited because of the heat which it produces

From a standpoint of both cost and efficiency, the use of a long core of small diameter rather than one of, for instance, half the length and twice the diameter is the more economical.

The cross sections of the magnetic paths, and hence the flux densities, in two such cores are the same; their radiating surfaces are practically the same because the heat is transmitted along the laminations, that is, to the edges and not through the ends; but the weight of the core of the larger diameter is twice that of the other and so its cost and losses are doubled. Doubling the diameter also increases the length of the end connections of the coils and this

results in an increase of the copper losses. However, changing the diameter of the core also involves other design changes. Retaining slots of the same size, the teeth will be twice their former width plus the width of a slot, and to obtain the same ratio of width of tooth to slot so as to maintain a uniform distribution of flux in the gap, the slot should be doubled in width. This increased size of slot will accommodate twice as many turns, and hence only one-fourth the original height of core will be required. With this arrangement, the same amount of copper will be required in the slot but considerably more copper will be required in the end connections than for the small diameter core. In other words, the weight of the core and the iron losses in the first and last designs will be identical, but the considerably increased amount of copper in the latter design will, due to the longer end connections, result in a corresponding increase in the cost and in the copper loss.

Various ratios, within certain limits, can thus be obtained between the core loss and the copper loss, but a detailed investigation will show the economy of cores of small diameter wherever this design is possible. The ratio of the length or height of a regulator core to its diameter is, however, limited by the space required for the winding and for a shaft of sufficient cross section to prevent vibration of the armature.

Design Limitations

A design embodying a long core of small diameter and wound two-pole has a greater tendency to vibrate than one with a short core wound four-pole because of the relatively longer distance between the bearings of the armature of a two-pole machine and because of the greater stability of a greater number of poles. However, with the

teeth and slots properly proportioned so as to maintain the same flux density in the gap for all positions of the armature and with a shaft, spider and bearings of proper design, the tendency to vibrate is reduced to a minimum and then depends chiefly upon the accuracy of the machine work and upon the materials used. The determination of the proper core and windings depends upon the voltage of the circuit to be regulated, the line current to be regulated, the voltage range required, the impedance of the windings, the magnetizing current, and the dissipation of the heat due to the losses.

A regulator for a large line current or one for a small voltage range may require a design which is not the most economical. For instance, some of the larger regulators require only a single turn for the series winding. As this is the minimum possible number of turns and as the next higher possible number is two turns, i.e., a 100 per cent increase, there is little choice in the selection of the most economical ratio between the amount of copper for the windings and the size of the sheet iron core. To limit the heating and the impedance drop in a high-current capacity regulator may require the use of a number of multiple-connected secondary conductors assembled in different slots. All such conductors must have the same phase relation, resistance and reactance so as to avoid local currents within the regulator. Hence, to obtain a sufficient section of copper to carry the current to be regulated, it may be necessary to use the four-pole design and to connect all poles in parallel. If, the current to be regulated were smaller, a two-pole design would probably be less expensive and more efficient.

The impedance of the winding is due to both the resistance and reactance voltage drops, and lowers the

voltage range of the regulator under load. Since the reactance depends in part on the square of the number of conductors per slot times the number of slots in series, its value can be varied by changing the number of slots and inversely changing the number of turns per slot.

The magnetizing current depends on the primary voltage and frequency, on the number of turns in the primary winding, on the magnetic flux density, and on the length of the magnetic path. It can be varied by changing the number of primary turns, the section of the magnetic path, or its length. A change in length, however, usually requires a change in the diameter of the core.

Both the impedance volts and the magnetizing current lower the power-factor. Their reduction to the lowest possible values, consistent with other requirements, is therefore desirable.

The dissipation of the heat due to the loss in the regulator depends upon the radiating surfaces, upon the amount of insulation on the coils, and upon the cooling medium. Their relation must be such that the cooling medium will keep the various parts of the regulator at a sufficiently low temperature to prevent injury to it. No difficulties are experienced in this respect with regard to the core, but the design of the windings must be given particular attention.

Eddy Current Losses

The losses in the windings are those due to the load currents flowing through the windings and to eddy currents (local currents induced in the windings by the leakage flux).

The eddy current loss in the windings is confined almost entirely to that portion of the copper embedded in the slots of the core. This loss depends not only upon

the cross sectional area of the conductor but also upon its shape, upon its disposition in the slot, and upon the frequency of the circuit. The importance of selecting the proper cross section for the conductor will become apparent from a consideration of the following illustration.

In a polyphase regulator, the eddy current losses in the slot portion of a winding made of flat conductor whose width is twice its thickness and whose area is 0.02 sq. in. are 2.5 times as great as the corresponding losses in a similar winding made of a conductor of equal area and square cross section. The losses in a winding made of a single conductor having a square section of 0.01 sq. in. are four times as great as those in a similar winding made by using a square-sectioned conductor of 0.02 sq. in. area and connecting two such conductors in multiple. Thus, by substituting two conductors of square section for a single rectangular conductor of the same area but having a ratio of 2 to 1 between its width and thickness, the eddy current losses can be reduced in the ratio of 10 to 1. As the ratio of width to thickness increases, the amount of the eddy current loss increases. A round wire gives the minimum loss. Because of the greater space required by round wire for a given area and because of the difficulty of winding a wire of square section, nearly all windings are made of rectangular wire, but wire of relatively small section is used. The use of a number of small wires in multiple, instead of a single conductor of equal section, increases the space required in the slot, and hence increases the size and cost of the core. The cost of the copper and of the winding is also increased. The increase in cost is, however, justified by the decrease in the loss.

In the single-phase regulator, the copper losses vary in a similar manner due to the use of conductors of different

shapes and sections, but the loss variation is not so great as in the three-phase design. The preceding comparison, however, emphasizes the necessity for carefully selecting the conductor for slot-wound alternating-current apparatus. It also shows the reason for using a stranded cable for the winding of the short-circuited coils in single-phase regulators, which coils are almost entirely in the slots of the core. Since the ohmic resistance of a wire of given length and area is the same regardless of the shape of its section, resistance measurements afford no indication of the losses. The losses are, nevertheless, evident in the heating of the machine under load and can be determined by the wattmeter method.

The copper loss as determined by the wattmeter represents the actual loss. This loss may show an increase, over the losses determined by the resistance method, of 5 to 10 per cent for small wire-wound machines, 10 to 25 or 30 per cent for medium sizes having coils wound with rectangular wire, and as high as 60 per cent for bar windings. The eddy current loss increases with the frequency. The percentage increase in the loss also depends upon the ratio of the length of the coil in the slot to the total mean length of turn of the coil.

Over Ratio

The ohmic and reactive resistance of the windings lowers the voltage and, hence, the range of the regulator. A low power-factor load further increases this voltage drop. The number of series turns is, therefore, always greater than indicated by the rated voltage ratio. This over ratio of turns is sufficient to produce the rated voltage range with full load of approximately 80 per cent power-factor.

Arrangement of Windings

The shunt windings of regulators are usually assembled on the movable core because the current in this winding is much less than in the series winding, and in the polyphase design there are fewer leads to the shunt winding than to the series coils. As the windings on the movable core must be connected to the circuit by some flexible connection (usually cable), this arrangement, from a mechanical viewpoint, is therefore the most convenient one. From the standpoint of insulation, this arrangement is disadvantageous, for the slot space in the rotor is less than in the stator, while the insulation required for the shunt windings, because of the greater number of turns in these windings, is greater than for the series coils. However, the arrangement is, in the majority of cases, the only feasible one because of the number and size of the leads of the secondary winding.

Y-Delta Connection

The shunt windings of single-phase and two-phase regulators are necessarily always wound for the full line voltage. Three-phase or six-phase regulators can, however, be wound for a lower voltage per phase by taking advantage of the Y connection of the phases, and all standard machines are so arranged. In the smaller sizes of the three-phase and six-phase regulators, the Y connection of the primary is an advantage in that the total number of turns is thereby decreased, the section of the conductor being proportionally increased. With the same amount of insulation on each conductor for both the Y and delta connection, the total insulation for the former is also less because of the smaller number of turns, and hence a smaller slot space is required. The reduction in the number of turns reduces the labor

cost and the reduction in the total insulation reduces the material cost without any sacrifice in the design or in the operation of the regulator.

Three-phase machines are frequently required for both Y and delta connections (usually for 4000- and 2300-volt circuits). This arrangement is desirable as it allows a standard 2300-volt line to be readily converted into a 4000-volt one by the Y connection of standard 2300-volt distributing transformers. This connection nearly doubles the kv-a. capacity of the feeder circuit but maintains the same voltage drop and same losses. Such an arrangement of the primary windings of the regulator does not, however call for a multiple-series arrangement of the series coil, for if the line current remains the same, the voltage drop also remains the same. For instance, if a 20 per cent voltage range is required in order to regulate the 2300-volt circuit properly, a range of only 11.6 per cent is required in order to obtain the same regulation on the same circuit when it is operated at 4000 volts. In other words, the actual voltage drop in the line remains as before and therefore no change is required in the series winding of the regulator.

In arranging regulators for either a delta or Y connection, it is necessary, however, to provide for the shift in the boost and lower positions due to the change from one connection to the other. In the maximum boost position of any regulator, the series winding for any phase must embrace the same pole as the shunt winding for that phase. This is indicated in Fig. 9 which shows a Y-connected shunt winding; that is, each shunt winding is excited by that phase of the line with which the series winding embracing the same pole is in series. Changing the connections of the shunt winding to delta, however, connects two shunt or excitation windings of the regulator to each

phase of the line. Thus, the voltage induced in each phase of the secondary winding is no longer due to a single shunt winding but to a combination of two of the shunt windings. In order to obtain the full boosting effect in the series windings, and to have it in phase with the line voltage, the

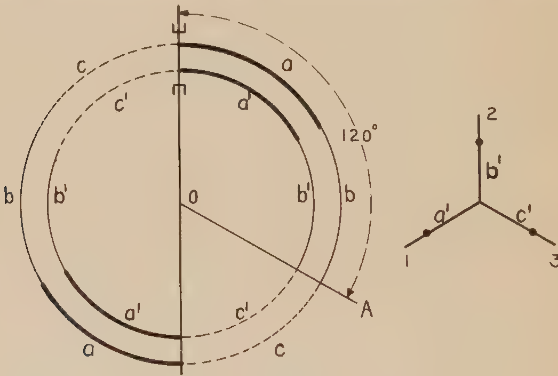


Fig. 21
Y-Delta Connection of a Three-Phase Regulator

rotor must therefore be shifted so that each series winding embraces that pole face which is embraced by the two shunt windings connected to each corresponding phase. The shifting must be done in the same manner as though the two phases constituted a single winding.

In a two-pole three-phase regulator, each phase winding occupies 60 degrees per pole, and the center of the pole of any phase passes through the center of the area embraced by that winding. The relative positions of the rotor and stator windings for a Y connection are shown in Fig. 21 in which *OA* indicates the center of the pole for phase windings *a′* and *a*, that is, for both the shunt and series windings connected to phase I of the line. If, however, the shunt windings are connected delta and shunt windings

a' and b' are both connected to phase I of the line, the center of the pole of this combination is shifted forward by 30 degrees. In other words, the center of the pole is now half way between the positions occupied by windings $a'a'b'b'$ as OA in Fig. 22. To obtain the boosting effect of

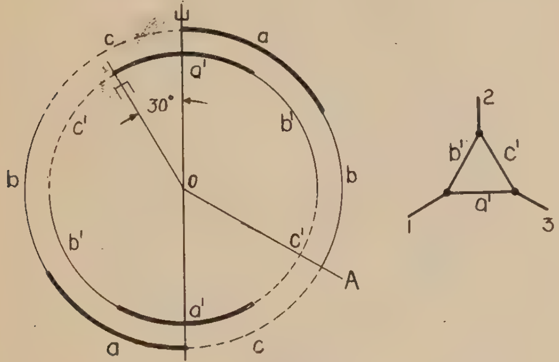


Fig. 22
Y-Delta Connection of a Three-Phase Regulator

the series winding in phase with the line voltage, the rotor must therefore be shifted backward by 30 degrees as shown in Fig. 22 so that the center line passing through the combination of shunt windings $a'a'b'b'$ again coincides with the center line of the series winding aa. It should be noted that all of these windings are now connected to phase I of the line. In regulators arranged for Y-delta connection, this requirement is usually taken care of by providing a worm gear segment of such length that the entire range can be obtained with either primary connection. The stop or trip pins on the segment must, however, be adjusted for each case to insure proper voltage regulation.

Design of Punchings

Fig. 23 shows a characteristic design of the laminations for the primary and secondary cores of a single-phase regulator of standard design. All slots in the armature

Fig. 23
Punchings for Single-Phase Induction Voltage Regulator

punching are of practically the same size and all are used for windings. A certain number, approximately one-half, are used for the shunt or exciting winding and the remainder are used for the short-circuited winding. Only a portion of the slots in the secondary core are, however, filled with windings. The area of the pole enclosed by the secondary windings always corresponds to the area of the pole enclosed by the shunt windings. The vacant spaces on the secondary core, however, are provided with slots as shown. These slots are of the same width as the active or wound slots but are of less depth. The slots in both rotor and stator are thus uniform and symmetrical at the air gap. The width of the slots and teeth (on both the rotor and stator) are so

proportioned that the air gap (and, hence, the flux density in the gap) is constant for all positions of the armature.

The uniformity of the air gap reduces the tooth torque. This reduces the tendency of the armature to vibrate. The reduction in the depth of the vacant slots reduces the core loss because it reduces the flux density in that portion of the core which is below the shallow slots. This reduction in the loss is very appreciable in the neutral position of the regulator. The vacant slots also serve as a means for obtaining a very effective circulation of the cooling medium.

The laminations for polyphase regulator cores are necessarily uniform and symmetrical with regard to the size of the slots. As a consequence, the core loss is constant throughout the range of control. To obtain a uniform air gap, the same precautions are observed as with the single-phase type of regulator. Regulator cores, as already noted, are made as small in diameter as both the windings and their insulation and the size of the shaft will permit. They are also operated at a magnetic density which is fairly high, especially at the roots of the primary teeth. To reduce the core loss to a minimum, the highest grade of silicon steel is used for the laminations. The thickness of the steel is generally 0.014 in., though where the design will allow (as in certain low-frequency machines), a greater thickness is occasionally used.

Voltage Surges in Windings

The regulator, being connected in series with the line, is subject to surges originating in either the station or on the line. These surges, in attempting to pass through the series winding, are distorted and distributed along the winding in a manner which depends on both the reactance and the electrostatic capacity of the winding. These two

constants are determined by the design of the regulator. The length of the secondary conductor is known; hence, the wave length within the series winding can be determined. From the wave distribution along the winding, the maximum difference of voltage within the winding can be obtained, and this maximum voltage determines what insulation should be used on the conductors and between the layers of the coils.

Fig. 24
Method of Making Crossovers in Spring Type Regulator Coils Showing Insulation Over Crossover

Layer Insulation

It is impracticable to insulate the turns and layers of a winding absolutely to insure against a breakdown, but the insulation should be of such value that the chances of an internal short circuit and a breakdown to ground are equal. For standard regulators, the insulation between the windings and the core usually has an instantaneous safety

Fig. 25
Spring Type Regulator Coil Showing Layer Insulation
(Bottom View)

factor which, referred to the line voltage, is about 10. By arranging the internal insulation as indicated, the safety factor (referred to the normal induced voltage of the regulator) may be as high as 500.

Line disturbances passing through the series windings induce similar surges in the shunt windings, and the shunt windings are therefore similarly insulated. In Fig. 24 is shown the method of winding the coils and the manner of arranging the insulation between layers, while in Fig. 25 a completed single-phase coil is shown. The layer

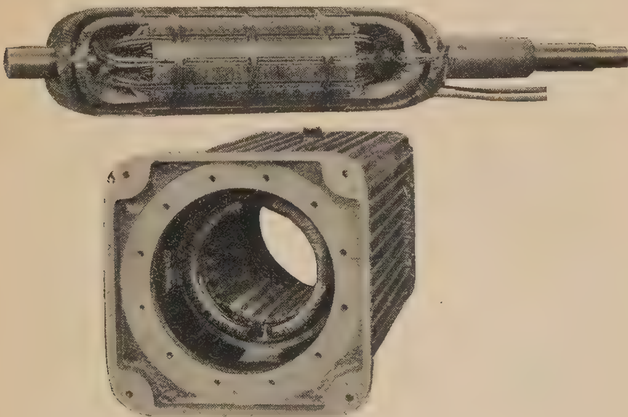


Fig. 26
Rotor and Stator for Single-Phase Induction Voltage Regulator

insulation extends beyond the windings and is folded over the edges. In the end portion of the coil, this insulation consists of varnished cambric. In the slot portion, it consists of horn fiber coated with shellac. The slot portion of the coil is placed in an adjustable mould for forming the coil to size. Press pieces which enclose an area of the exact size of the winding space are placed around the coil and the mould is then heated so as to melt the shellac on the layer insulation. The coil is then pressed to size, and after the form has been cooled, is removed from the mould. The layer insulation is coated with sufficient shellac to insure thorough impregnation of the slot portion of the coil. When the coil

comes out of the mould it is as hard and firm as a solid piece of insulation. After moulding, the coils are insulated according to requirements and are then ready to be assembled in the slots of the core for which they were designed.

Fig. 27
Nose of Polyphase Regulator Coil

Coil Design

Since the single-phase machine has only one phase winding per pole, coils of much simpler design can be used for the smaller sizes of single-phase regulators than are required for direct-current or polyphase machines. Fig. 26 shows a rotor and stator of a single-phase regulator of a standard size. It will be noted that, in the rotor, there is only one coil per slot. This results in economy of space for insulation and provides a very rigid coil. The stator coils are similarly arranged. Fig. 26 also shows the arrangement of the short-circuited winding which, as previously stated, consists of a stranded cable wound directly on the armature body. In the secondary or stationary core, the slots corresponding to those used for the short-circuited coils on the rotor are shown vacant and of less depth than those used for the winding. The reduction obtained in the core loss by this arrangement is of considerable advantage, for the reason that this loss exists 24 hours a day and any reduction of it is of value.

One end of a barrel type of coil used in the polyphase design of regulators is shown in Fig. 27 which illustrates the method of arranging the insulation between layers and especially at the end or nose of the coil. The insulation between layers in the slot portion consists of tough hard paper or horn fiber, and at the ends, of flexible varnished material. All layer insulation is of sufficient width to fold over the edge of the winding layer. The method of winding and insulating is the same as for the single-phase design of coil. Fig. 28 shows the completely assembled rotor and stator of a polyphase regulator.

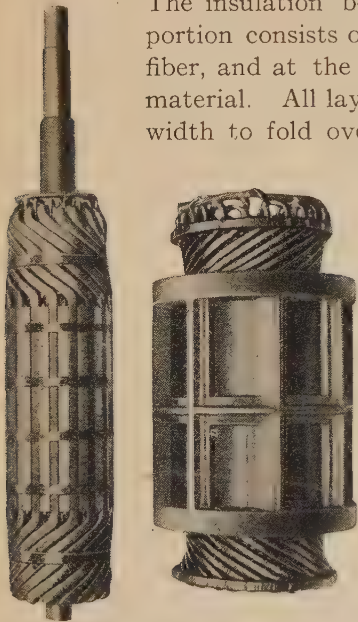


Fig. 28
Rotor and Stator of Polyphase Regulator

The larger sizes of single-phase regulators also use coils of this same design. A certain number of these coils on the armature are used for the active or shunt winding and the rest for the short-circuited winding. Such regulators have also a certain number of slots on the stator which are without winding as in the standard single-phase design.

All rotor coils are held in place by banding wire, and are securely braced at the ends, whereas all stator coils are held in place by treated hardwood wedges and by bracing and cording at the ends, as shown in Figs. 26 and 28.

SECTION VI

DESIGN CHARACTERISTICS

The fundamental requirement of a voltage regulator is to produce a gradual change in the line voltage. The ideal condition is to produce the voltage change at a uniform rate and independent of the load, of the character of the load, or of the line. The characteristics of any translating device will, however, change ideal conditions to some extent. For the induction regulator, such characteristics are: the mechanical design; the resistance and the reactance of the windings; and the magnetizing current. Their effect is modified by the characteristics of both the line and the load.

The distribution of the flux across the pole face causes the flattening of the curve at the maximum boost and maximum lower position, as shown in Fig. 6, but it also insures the smoothness of the curve throughout its length. The change in voltage per degree of rotation, while less at the extremes than in the center, is, however, in no way detrimental to the operation of the regulator.

Voltage at Neutral

As stated, the secondary voltage induced in a single-phase regulator is always in phase with the line voltage, while midway between the maximum boost and maximum lower positions the voltage is zero. This phase characteristic of the voltage allows the use of independently operated single-phase regulators on loop systems. When so used, the current in each feeder is directly proportional to the voltage and inversely proportional to the impedance of the circuit.

With the regulator in the zero voltage position, the secondary winding can be short-circuited and it can then be readily connected in or out of a feeder circuit without interrupting the service.

Parallel Operation

Due to its rotating field, the polyphase regulator, however, cannot be so handled. Fig. 29 shows the generator voltage and the resultant feeder voltage with the regulator

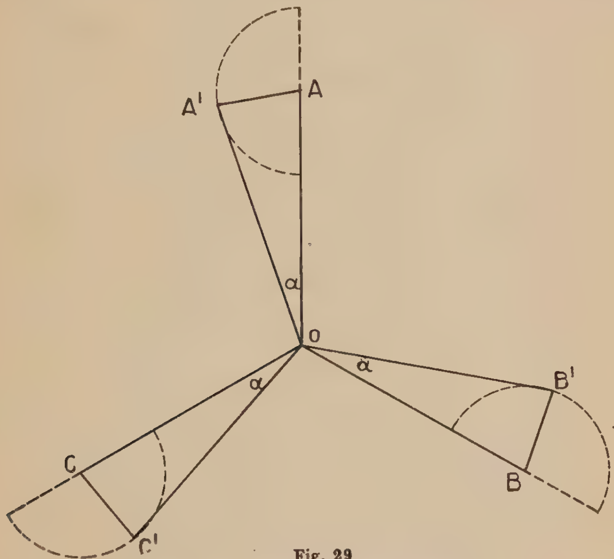


Fig. 29
Three-Phase Regulator Vector Diagram

in the neutral position. The generator voltage is represented by ABC and the feeder voltage by $A'B'C'$. The regulator voltage is AA', BB' and CC'. The phase displacement between the generator voltage and the feeder voltage is angle α.

The possibility of varying angular voltage displacements between individually controlled feeders prohibits the interconnection of feeders controlled by polyphase regulators unless the regulators are mechanically coupled. Such coupling is necessary in order to insure that the

feeders will always be in phase so as to avoid idle circulating currents due to phase displacement. The diagram shows the feeder voltage as equal to the generator voltage, although it will be observed that the full induced voltage

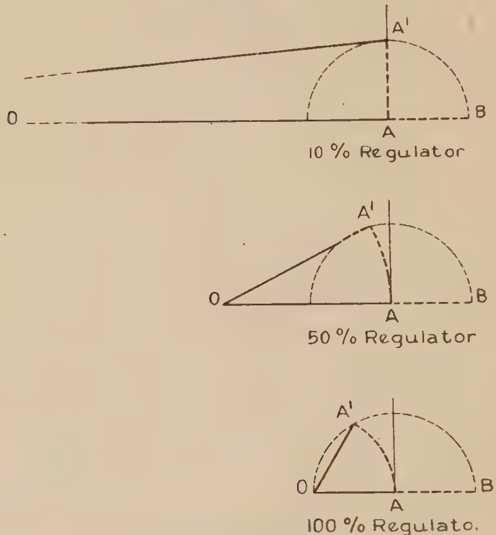


Fig. 30
Vector Diagrams Showing Position of Neutral in Polyphase Regulators

exists across the secondary of the regulator. For this reason, the secondary of a polyphase regulator cannot be short-circuited as this would result in a short circuit of both windings. It also will be observed that the neutral is not at the central point of the rotation of the armature. The location of the neutral point depends upon the per cent boost for which the regulator is designed.

This is illustrated in Fig. 30 in which all diagrams show the regulators in their neutral positions. OA is the generator voltage and is equal to the feeder voltage, OA'. Position A'

of the rotor is the zero or no-boost no-lower point. The voltage induced in the secondary of the regulator is AB. This voltage has a constant numerical value and revolves around A as the regulator armature is rotated from the

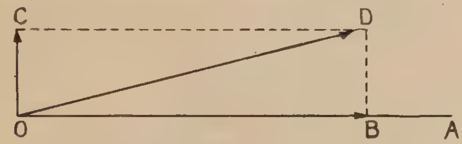


Fig. 31
Voltage Drop in Regulator Due to Load Current

maximum boosting to the maximum lowering position. Point A' in each case gives the position of the segment

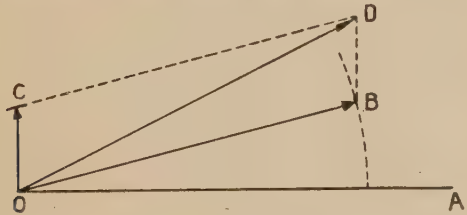


Fig. 32
Voltage Drop in Regulator Due to Load Current

with reference to the center of the worm when the regulator is in the neutral position.

Inherent Regulation

The resistance drop in the windings is always in phase with, and the reactance drop at right angles to, the current flowing. The magnetizing current, neglecting core loss current, is at right angles to the impressed voltage. These factors all tend to lower the effective voltage as indicated in Fig. 6. The drop in voltage, however, depends upon the load and the power-factor of the load.

The resistance drop, and hence the copper loss, is due to both the magnetizing current and the ratio current in

the primary winding, to the load current in the secondary winding, and also to the eddy currents (which depend on the cross section of the conductor) in both windings. These

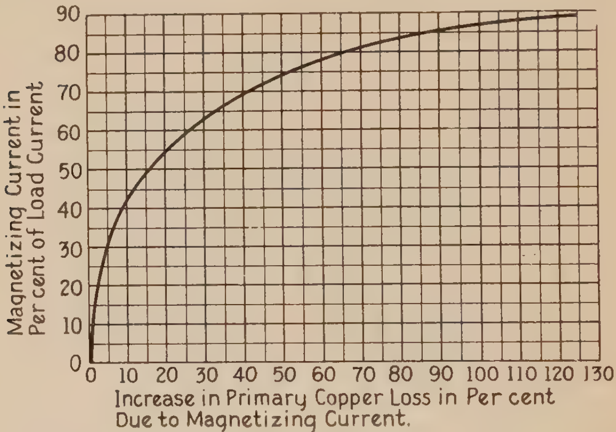


Fig. 33
Relation Between Magnetizing Current and Primary Copper Loss

considerations again emphasize the importance of using a proper copper section for the windings, and of designing the regulator for a reasonable magnetizing current.

At 100 per cent power-factor, the energy current is in phase with the voltage as shown in Fig. 31 in which: *OA* represents the voltage; *OB* the ratio current; and *OC* the magnetizing current. The resistance drop in the primary winding, as well as the copper loss, is then due to the resultant or load current which is represented by *OD*. Due to the power-factor of the load and the reactance of the regulator, as well as that of the feeder, this load current lags behind the voltage and increases the length of the line *OD*, as indicated in Fig. 32. Hence, the voltage

drop and the losses are increased as the power-factor is decreased.

With the regulator in the maximum position and carrying full load of 100 per cent power-factor, the increase in

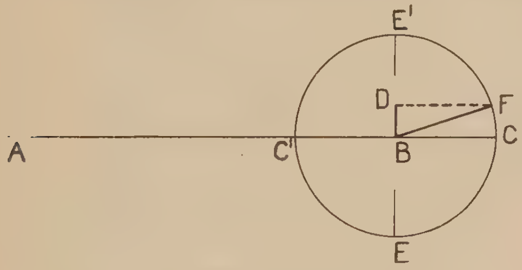


Fig. 34
Relative Losses in the Primary Winding with Ratio Current Rotated in Both Directions

the losses in the primary winding due to the magnetizing current is shown in Fig. 33. From the curve shown, it will be noted that with a magnetizing current greater than 40 per cent the primary copper loss increases rapidly as the magnetizing current increases.

Primary Current

As the regulator is rotated out of the maximum position, the ratio current of the single-phase regulator decreases as shown in Fig. 7 and that of the polyphase regulator, while remaining constant, changes its phase relation as shown in Figs. 15 to 19 inclusive. In the neutral position of the single-phase regulator, the primary copper loss is then due to the magnetizing current only, and in the polyphase type, to the resultant of the magnetizing current and ratio current. Depending upon the phase rotation, in the polyphase design of regulator, this resultant may be the sum or the difference of the two currents as indicated in Figs. 34 and 35.

Assuming 100 per cent power-factor and AB the line current, BC the ratio current of the regulator, and BD the magnetizing current at right angles to it; then, as previously demonstrated, the current BC rotates from the position shown in Fig. 34 to the position BC' as the regulator

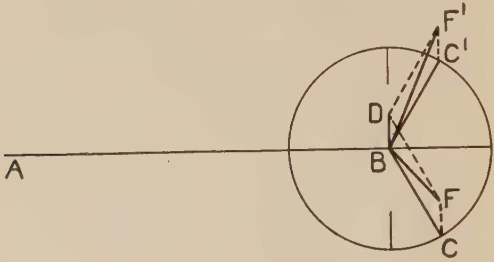


Fig. 35

Relative Losses in the Primary Winding with Ratio Current Rotated in Both Directions

armature is rotated from the maximum boosting to the maximum lowering position. This current may be caused to rotate through either E or E' by rotating the armature either to the right or left, or by reversing the phase rotation in the regulator by reversing the leads, as is done in reversing the rotation of an induction motor. The magnetizing current BD remains fixed in position and value, and for any given load on the feeder, the value of BC remains constant. The resultant or primary current BF will, however, depend on the direction of rotation of BC as shown in Fig. 35. As shown in this illustration, if the ratio current is rotated to the left, the resultant primary current BF' increases in value as the regulator is rotated toward the neutral position, whereas if rotated to the right, the resultant primary current BF has a smaller value for all corresponding positions except at maximum boost or lower.

Fig. 36 shows the relative losses in the primary winding with the ratio current rotated in both directions and with a magnetizing current of 25 per cent. It will be observed that, although in the extreme positions of the armature

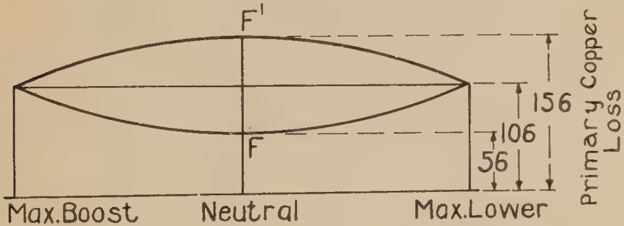


Fig. 36
Relative Losses in the Primary Winding with Ratio Current Rotated in Both Directions. Full-Load Condition.

the primary copper loss is the same in either case, this loss is nearly three times as much for left-handed as for right-handed rotation when the armature is in the neutral position.

While a high magnetizing current is obviously a disadvantage and a source of loss when the regulator is in either of the maximum positions, it might seem that this does not apply in a polyphase machine as the armature is rotated toward neutral. This is not the case, however, because the ampere-turns in the primary should always equal the ampere-turns in the secondary. Any discrepancy results in an impedance voltage drop. For instance, if the magnetizing current were to equal the full-load ratio current, and the regulator were in mid-position with full-load current in the series winding, then the resultant current in the primary winding would be zero. The load current would then act as the magnetizing current, and as this current has been assumed to be 100 per cent at full voltage, the full secondary voltage of the regulator would be required to force the load current through the regulator.

Under this conditon, the regulator would be a series reactance, and not only would the boost and lower curve be distorted and irregular, but the power-factor of the line also would be lowered.

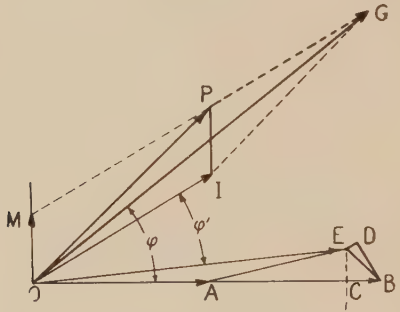


Fig. 37

General Vector Diagram of the Inherent Regulation of a Regulator

Impedance

The impedance of the windings lowers the effective voltage of the secondary and changes its direction with regard to the line voltage. This is indicated in Fig. 37 which is a general diagram showing the effect of the ohmic and reactive resistance, and in which

OA = the generator voltage,

AB = the secondary voltage of the regulator at no load,

OI = full-load line current (and also the primary ratio current for a 1 to 1 winding),

OM = the magnetizing current at right angles to the generator voltage OA; and, then,

OP = the total primary current, being the resultant of the ratio current OI and the magnetizing current OM, and

OG = the generator current, being the resultant of the load current OI and the regulator primary current OP,

BD = the combined reactance drop of primary and secondary. (The drop across each winding is at right angles to the respective current in each winding.)

ED = the combined ohmic drop. Then,

EB = the impedance of the regulator,

AE = the resultant secondary voltage at full load,

OE = the feeder voltage, and

CB = the total voltage drop in the regulator.

Power-Factor

The cosine of the angle φ (Fig. 37) represents the power-factor on the generator side, and the cosine of φ' the power-factor of the load. The power-factor of the former is lower, due to the magnetizing current and the reactance of the regulator.

The diagram (Fig. 37) also shows the effect of the power-factor of the load on the impedance voltage drop in the regulator. The higher the power-factor of the load the higher will be the power-factor of the generator and the lower the voltage drop in the regulator.

Referring to the diagram, as the angle φ' decreases, the angle φ decreases also. As these angles decrease, the impedance voltage EB rotates to the right about B as a center. This increases the effective regulator voltage AE or in other words, decreases the effect of the impedance voltage drop of the regulator on the line voltage.

Fig. 37 represents conditions in a regulator having a secondary voltage equal to the line voltage. For clearness of illustration, the reactance of the regulator is also purposely

exaggerated. Normally, the values of the ohmic and reactive drops would be so small compared with the line voltage as to be unintelligible on so small a diagram. For the same reason, the combined reactance and resistance of both primary and secondary windings is shown, although

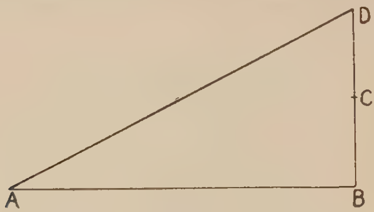


Fig. 38
Determination of Power-Factor of a Regulator

preferably each should be shown independently with reference to the current in each winding, and afterwards combined so as to show the total impedance of the regulator.

As indicated, the power-factor of the regulator lowers the power-factor of the system, but as a normal regulator has a kv-a. capacity of only one-tenth of that of the feeder controlled, its effect on the line is not serious. It also will be noted that the effect of the power-factor of the regulator on the line voltage decreases as the voltage range of the regulator decreases and as the power-factor of the load increases.

Fig. 38 gives a method for approximately determining the power-factor of the regulator. When the power-factor has been determined, its effect on the line can readily be ascertained.

Assuming the voltage and the full-load current of the regulator to be 100 per cent each, and letting:

AB be the energy component (that is, the current times voltage in per cent).

BC the wattless component due to reactance (that is, current in per cent times total reactance in per cent, the reactance being expressed in per cent of the voltage of the primary winding. This reactance voltage is at right angles to the load current and voltage).

CD the wattless component due to the magnetizing current (that is, line voltage times magnetizing current in per cent, the latter being at right angles to the line current and voltage), then

AD represents the kv-a. and

AB the kw. of the regulator, the power-factor being AB divided by AD.

In other words, the base line AB may be considered as 100, BC the reactance, and CD the magnetizing current, each expressed in per cent. The power-factor of the regulator will then be the ratio of 100 to AD.

Assuming the reactance to be 20 per cent and the magnetizing current 30 per cent, the power-factor of the regulator is 86.5 per cent. Assuming a 10 per cent regulator, the value of BD with reference to the line is one-tenth of $(20+30)$ or 5, and since the line is equal to 100, the 100 per cent power-factor of the line is reduced to 99.9; that is, for the case cited, the regulator reduces the power-factor of the line about one-tenth of 1 per cent.

Over Ratio

As previously stated, the greater the voltage range of the regulator and the higher its magnetizing current and impedance with respect to the line, and the lower the power-factor of the load, the greater will be the internal voltage drop in the regulator, and the greater will be the lowering of the power-factor of the line by the regulator. The

internal voltage drop can be compensated for by an over ratio of turns in the series winding; but there is no means of compensating for the lowering of the power-factor of the line.

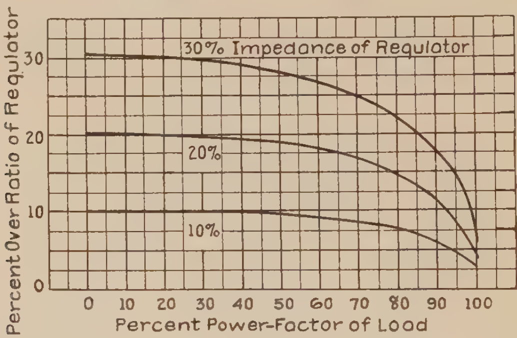


Fig. 39
Required Over Ratio of Regulator to Compensate for Various Power-Factors of Load

Fig. 39 shows the over ratio required in the series windings of regulators having different impedances when carrying full load of various power-factors. The result of the internal voltage drop in the regulator is shown in Fig. 6, this curve showing that the total voltage range is not decreased but that the entire regulation curve is lowered. As voltage regulation requirements usually demand the maximum boosting effect at full load, the regulator is always designed with a sufficient over ratio to meet this condition. The over ratio is, however, not indicated in the rating of the regulator. The rating is always based on the full-load boosting requirement so that, when the regulator is in this position, the no-load ratio or the secondary induced voltage of the regulator may in some cases be considerably in excess of the rating as indicated by the name plate.

Torque

The angular or rotating torque of a regulator armature may be considered as being due to the tooth torque and to the load torque. The tooth torque is produced at no load

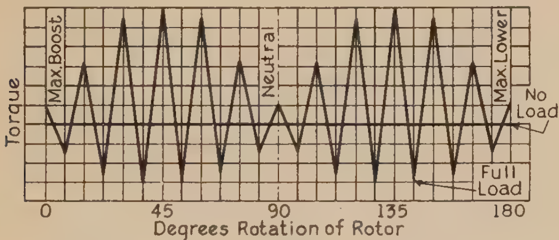


Fig. 40
Tooth Torque of a Single-Phase Regulator

when, because of improperly designed teeth and slots, the magnetic flux density at the gap is variable for different positions of the armature, and at full load because of the distortion of the flux regardless of the tooth design. The tooth torque under load may be represented by Fig. 40, and in such a curve, the number of maximum and minimum values will be dependent upon the number of teeth in the rotor and stator.

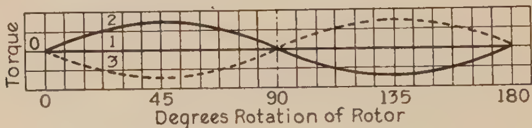
The load torque may be regarded as being produced by the reaction between:

The secondary current and the primary flux;
The primary current and the secondary leakage flux;
The short-circuit or compensating current and the secondary leakage flux.

The magnetic field due to the ampere-turns of any winding may be regarded as being counterbalanced by the magnetic field due to the ampere-turns of the ratio current in any other winding which is in direct inductive relation

to it. The torque may be regarded as being due to the ampere-turns of any winding directly in the field produced by some other winding.

With the armature of a single-phase regulator in either maximum position, the load torque is zero for any power-



1. Torque Due to Primary Flux and Secondary Current.
2. Torque Due to Secondary Flux and Primary Current.
3. Torque Due to Secondary Flux and Short-Circuit Current.

Fig. 41

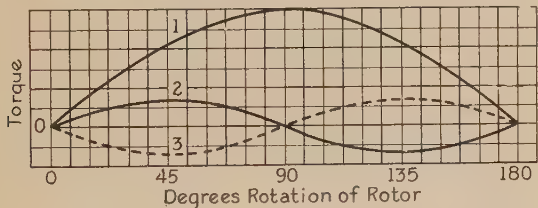
Regulator Torque at 100 Per Cent Power-Factor Load (Single-Phase)

factor load. In either of these positions, both the rotor and stator coils embrace the same flux, and while the repulsion between them depends on and is proportional to the current flowing, the tendency to rotate is zero. The short-circuited winding has no effect in these positions, for the current in this winding is zero.

With the single-phase regulator in the neutral position and with 100 per cent power-factor load, the load torque is again zero. The series winding is cut by the maximum primary flux but the current in this winding is zero at the maximum flux wave and the flux is zero at the maximum current wave. Midway between these points each has definite values. However, the direction of the torque changes twice for every cycle, and so the resultant is zero. With the regulator in the neutral position, but with zero power-factor load, both the current in the series winding and the flux due to the primary winding have their maximum values at the same instant of time and they both reverse at the same instant of time. The load torque

therefore is a maximum for this condition and has a direction tending to rotate the armature to either extreme position of the regulator where the torque is zero.

With the regulator armature under load and midway between the neutral and either maximum position, both



1. Torque Due to Primary Flux and Secondary Current.
2. Torque Due to Secondary Flux and Primary Current.
3. Torque Due to Secondary Flux and Short-Circuit Current.

Fig. 42

Regulator Torque at Zero Power-Factor Load (Single-Phase)

the primary ampere-turns and the short-circuited ampere-turns are partly in the flux path produced by the load current in the series winding. As the leakage flux is in phase with the load current, and therefore is out of phase by 180 degrees with the ratio currents in the shunt and short-circuited windings, both have positive values and a corresponding torque results. This torque is in one direction on one side of the neutral, and in a reverse direction on the other side. However, the torques due to the two windings are opposite, and so the resultant torque is zero; this applies to loads of any power-factor. These conditions may be illustrated by Figs. 41 and 42.

The windings on the rotor are displaced 90 degrees from each other, and with the armature in the position considered, each is displaced 45 degrees from the series coil. Since the windings are not in direct inductive relation to each other, they cause the resultant flux to be distorted

and not uniform as considered. The distortion is a maximum in this position of the armature and, therefore, the tooth torque is a maximum as indicated in Fig. 40. This tooth torque is superimposed on the regulator torque shown in Fig. 42. The regulator torque due to the secondary current and the primary flux always exists, for no regulator operates on a 100 per cent power-factor load. With the ordinary commercial load, the torque is therefore always greatest half way between either maximum position of the regulator and the neutral position. As a result, this position is the one at which the regulator is most likely to vibrate, and the lower the power-factor of the load, the greater is this tendency.

At 100 per cent power-factor load, the torque in a polyphase regulator is maximum at either extreme and is zero at neutral. Referring to Fig. 15, the torque is not due to the reaction between the currents in phase I of the primary and phase I of the secondary, but is due to the flux produced by phase I of the primary and the ampere-turns in phase II of the secondary, and also to the primary flux of phase II and the secondary ampere-turns of phase I. In point of time, the maximum flux value due to the primary of phase I occurs 90 degrees from the maximum load current value in this phase, that is, in phase with the maximum current value in phase II.

Thus, phase II, being in the path of the flux due to phase I, has its maximum torque in this position. The action of the primary of phase II on the secondary of phase I is identical. In Fig. 17, which shows the armature in the neutral position, the secondary ampere-turns of phase I are in the path of the flux generated by phase I of the primary, but as the maximum of the flux wave is 90 degrees from the maximum load current wave, the flux is

zero at maximum current and is maximum at zero current. The torque is therefore zero. Midway between the maximum and neutral positions (see Figs. 16 and 18), the torque due to the flux of the primary of phase I and the

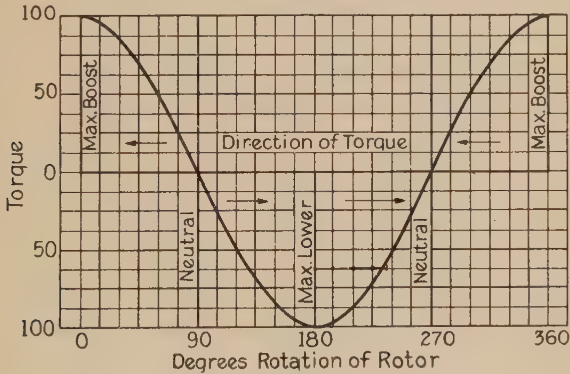


Fig. 43
Polyphase Regulator Torque

secondary ampere-turns of phase I is still zero. Nevertheless, torque is produced by the flux of phase I of the primary and the series ampere-turns of phase II, but in less degree than in either maximum position. The reason for this is that the ampere-turns of the secondary of phase II are only partly in the flux path of phase I primary. The action of phase II primary on phase I secondary is similar. The resultant torque curve is shown in Fig. 43.

With the regulator in either maximum position and with zero power-factor load, the torque is zero. However, it is a maximum in the neutral position because in point of time the maximum flux wave remains as before, but the maximum current wave in the series winding is shifted by 90 degrees. When, in Fig. 15, the flux wave due to the primary of phase I is a maximum, the current in the series winding of phase II passes through zero and the torque is

zero; whereas, in the neutral position (Fig. 17), when the flux wave of the primary of phase I is a maximum, the current wave of the secondary of the same phase is a maximum also. This results in a maximum torque in this position.

An analysis of the intermediate conditions will show that, in a polyphase regulator, the maximum torque is constant for any given load current regardless of the power-factor of the load, but the position of this maximum point with reference to the position of rotor to stator shifts with the power-factor of the load. Due to the relative reversal of the direction of the primary flux with respect to the secondary ampere-turns, resulting from passing through the neutral position, the direction of the torque is also reversed. The regulator tends to rotate either from or toward the neutral position of the segment in accordance with the law governing the direction of movement of a conductor carrying a current flowing in a given direction when the conductor is in a magnetic field of a given direction.

As the current in an alternating-current system constantly changes in value and direction following a sine wave and as the resultant flux, produced by the combination of the fluxes of the individual phases, rotates (both of which conditions are shown by Figs. 10 to 14), the foregoing presentation is necessarily based on instantaneous values of current and flux. The total torque produced is, however, the resultant of the torques due to the action of each individual primary phase on some secondary phase. As the flux and current values increase and decrease successively as shown in Figs. 10 to 14, the total torque value for any one position of the regulator is therefore constant, and in a given direction, for any given secondary current and power-factor of the load.

The maximum value of the torque is equivalent to that of a motor or generator of the same voltage, current, and frequency, and wound for the same number of poles. Were the secondary windings of the regulator short-circuited and the primary windings supplied with normal voltage, the armature would rotate and develop torque as an induction motor. Since, however, the secondary windings are connected in series with the line, and since the currents in these windings are determined by the load on the line and not by the voltage induced in these windings, the resultant torque for various positions of the armature is as illustrated instead of being constant and in one given direction as in a motor.

The torque due to the secondary leakage flux and the load currents in the various primary windings is zero. In this respect, conditions are similar to those in the single-phase regulator. The flux distortion due to the load also produces similar distortions in the tooth torque.

This tooth torque is superimposed on the rotating torque, so as to make this line irregular instead of smooth as shown.

The tooth torque due to load is rather appreciable in all regulators because of the small number of wide teeth and slots. It could be greatly reduced by an increase in the number of teeth, or by the use of overhung slots. The increased expense of so doing is, however, not justified by the results obtainable and, furthermore, the torque can readily be taken care of by properly designed mechanical parts. The rotating torque is, however, a characteristic which cannot be modified or changed by any change in design. It is a disadvantage in the regulator but it can also be taken care of by properly designed mechanisms and operating motors.

SECTION VII

MECHANICAL DESIGN

All modern regulators are of the vertical type shown in Fig. 44 and have the shunt windings assembled on the rotor and the series windings assembled in the stator. Except in four-pole machines, the primary core is usually assembled directly on the shaft and the secondary core in a rigid and substantial cast iron tank or spider. The shaft is of exceptionally heavy construction and is supported in bronze bearings of liberal design. The laminations constituting the secondary core are held in place by heavy flanges which are keyed to the spider by circular keys; the laminations of the primary core are held by similar flanges. When the primary core is assembled directly on the shaft, the upper flange is held in place by a shoulder on the shaft and the lower flange is keyed. When assembled on a spider, the core is clamped by bolts through both flanges, and is supported by a shoulder on the shaft and under the lower flange. The shaft is brought out through the cover and is keyed to a heavy segment by means of which the armature is rotated.

A large number of regulator parts such as spiders, tanks, covers, cores, mechanisms, etc., have been developed and standardized. Each tank or spider is designed for several heights or lengths of core. As a result, practically all requirements for regulators from 100 watts to 1000 kv-a. and for circuits for any phase, frequency, or voltage for which regulators are usually designed can be satisfied by the use of standard parts.

Tanks and Spiders

Two standard designs of tanks and spiders have been developed, namely, the cast iron ribbed tank shown in Fig. 45; and the skeleton frame shown in Fig. 46. The

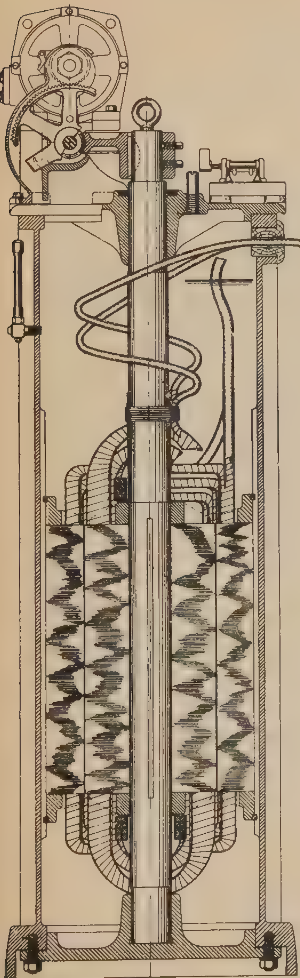


Fig. 44
Assembly of Single-Phase Feeder Voltage Regulator

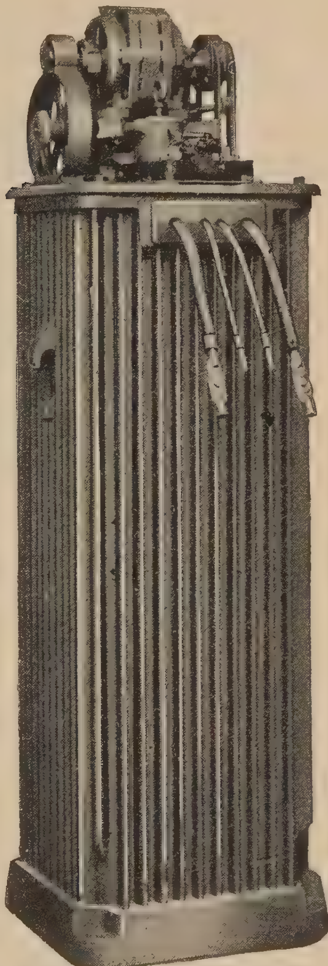


Fig. 45
Type IRS Induction Voltage Regulator

former is used for standard self-cooled regulators having capacities up to about 60 kv-a. The latter is used for regulators of larger capacities as well as for the oil and water-cooled and the forced-oil types. The majority of

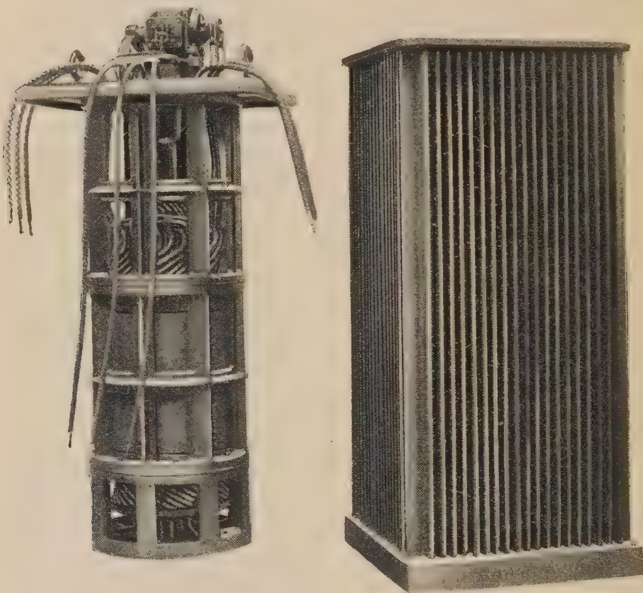


Fig. 46
Spider of Three-Phase Oil-Immersed Self-Cooled Regulator, Removed from Tank

regulators are assembled in the cast iron ribbed tank of which a number of sizes have been developed. These tanks are extremely rigid and substantial, and because of the large number used, special appliances have been designed for their manufacture.

Fig. 47 shows one of the moulding machines developed for this design of tank, and Fig. 48 shows the core box. As indicated in Fig. 47, only the cast iron pattern and

stripping plate are above the foundry floor. The pattern is adjusted above the floor to the height of the tank wanted and is surrounded by a flask of the proper height.

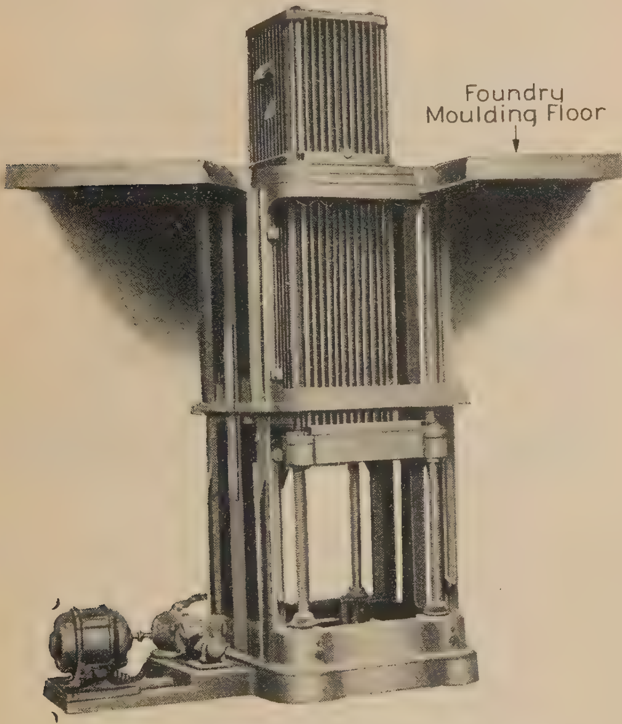


Fig. 47
Moulding Machine for Regulator Tank. (Tank Casting 25 In. Square, 72 In. High, Weight 2000 Lb.)

This flask is filled with sand which is rammed in pneumatically. After this has been done, the pattern is drawn through the stripping plate into the basement below by means of the motor-operated mechanism shown. The core is made in a split core box as shown in Fig. 48. The

spider casting is made with the top of the tank up so as to give the greatest weight and the densest metal at the bottom where it is most needed. Made with the equipment shown, castings of a high degree of excellence are obtained.

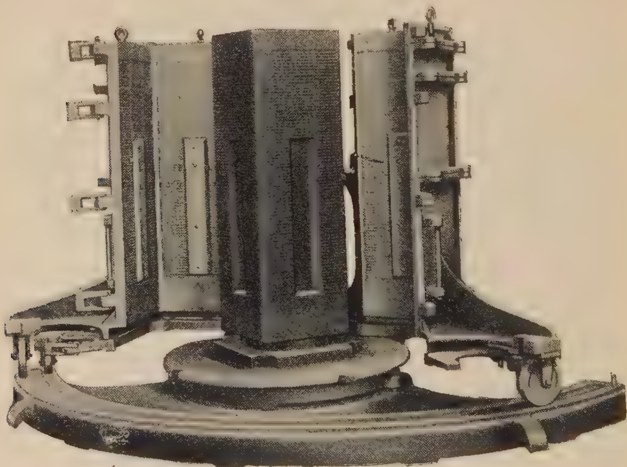


Fig. 48
Core Box with Core for Regulator Tank. (Tank Casting 25 In. Square, 72 In. High, Weight 2000 Lb.)

The tanks are machined on a special boring mill shown in Fig. 49. The boring of the inside and the facing of both ends are done simultaneously. By referring to Fig. 44, it will be noted that the diameter for the bottom and that of the cover-fit correspond to the outside diameter of the core. This arrangement, with the method of machining used, gives very satisfactory results.

The bottom of this design of tank is a separate casting which is bolted on by means of studs and nuts. The bottom fits into the tank without any clearance, the holes for the studs are not drilled through the tank, and the contact surfaces are thoroughly leaded before assembling.

Tanks of this construction have been used for a number of years, and if properly assembled, will not leak. In assembling, it is necessary only to draw up the bottom uniformly so as to insure a square seat.

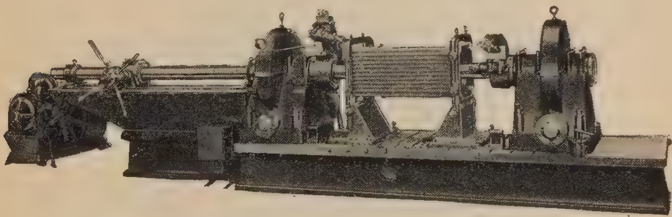


Fig. 49
Boring Mill for Induction Regulator Tanks

The cover is simple in design and has all machined surfaces for the operating mechanism in one plane. The bearings in both bottom and cover are bronze lined and are renewable if this should become necessary.

This design of tank, bottom and cover and the manner of machining insure, not only maximum rigidity, but also concentricity between the rotor and stator. Where applicable, the cast iron tank is preferable to the spider type because it has a smaller number of parts, it occupies less floor space and contains less oil. However, its use is limited to the smaller sizes of regulators due to the difficulties of casting larger sizes of tanks than standardized and because of further difficulties in obtaining a sufficient radiating surface on the larger tanks to satisfy operating temperature requirements.

In the larger sizes, the skeleton spider shown in Fig. 46 is usually made in sections which are securely bolted together. This is done because of the difficulty of casting, machining and assembling, in a single piece, spiders of considerable height and comparatively small diameter. The various sections are designed for the maximum strength and rigidity consistent with minimum weight. They are machined on

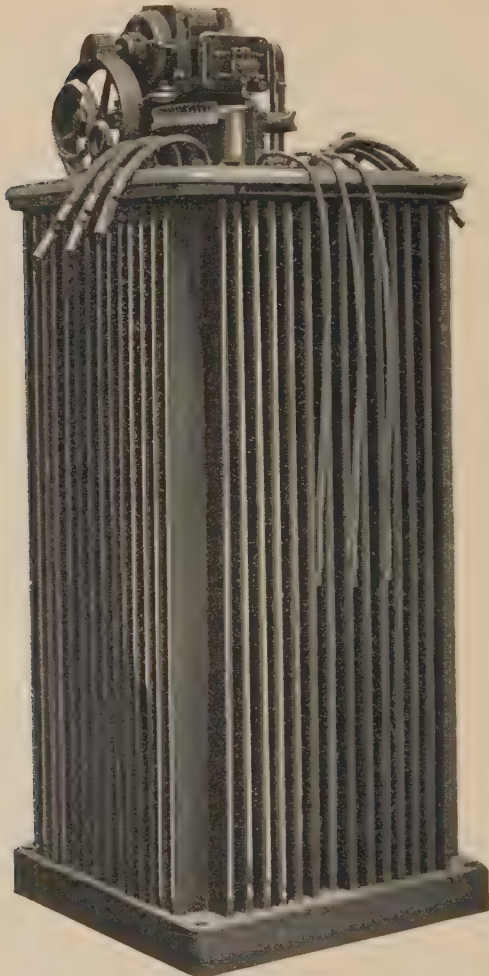


Fig. 50
Three-Phase Self-Cooled Automatic Induction Voltage Regulator

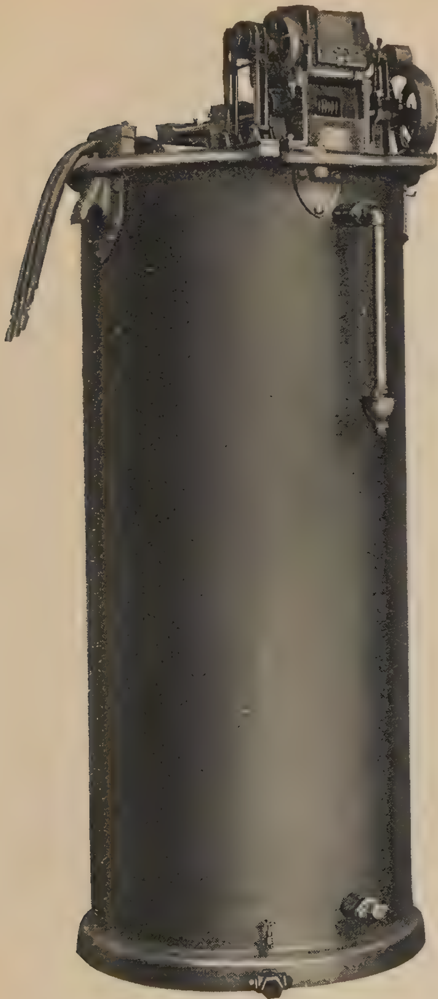


Fig. 51
Three-Phase Oil-Immersed Water-Cooled Motor-Operated Induction Voltage Regulator

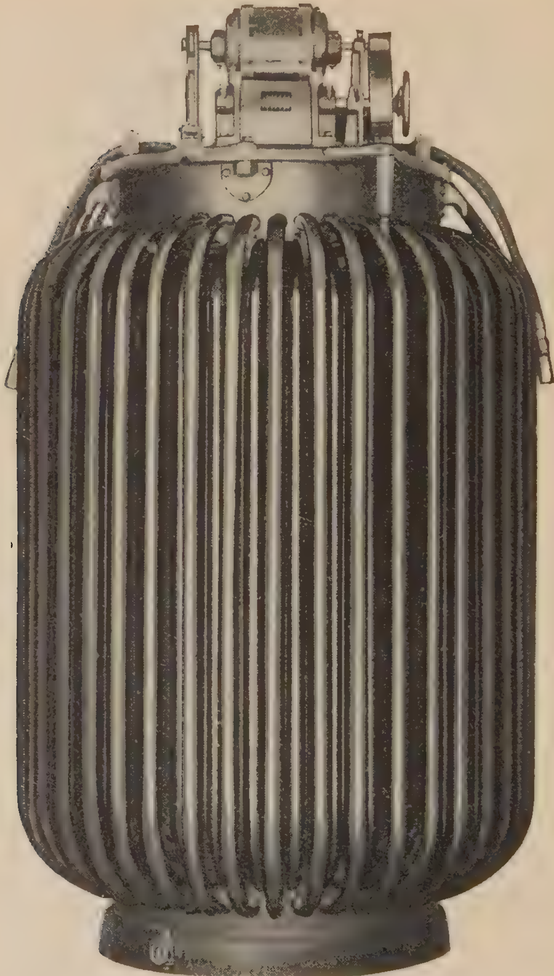


Fig. 52
Three-Phase Oil-Immersed Self-Cooled Motor-Operated Induction Voltage Regulator

Fig. 53
Three-Phase Air-Cooled Motor-Operated Induction Voltage Regulator

a vertical boring mill and then assembled and rebored to insure the proper alignment of parts.

This design of spider may be provided with a square cover and suspended in a corrugated sheet iron tank as shown in Fig. 50. When so constructed, it is used for a self-cooled regulator. It may be provided with a round cover and assembled in a boiler plate tank as shown in Fig. 51. When assembled in this manner, it is used for an oil- and water-cooled or for a forced-oil regulator. Again, it may be assembled in a tubular tank and used for a self-cooling regulator, as shown in Fig. 52. The cover for the skeleton spider design is made in the same manner as for the cast iron tank, and both top and bottom bearings are bushed with bronze linings.

The corrugated tank shown in Fig. 50 is electrically welded at the seams and the corrugations are cast into the base. All boiler plate tanks, whether of the type shown in Fig. 51 or Fig. 52, are electrically welded.

All cast iron tanks are provided with pipe plugs for the drainage of oil, but all other designs are furnished with valves. Oil gauges to show the proper level of oil are provided on all tanks.

Although the majority of regulators are oil-immersed, there is an occasional demand for the forced air-cooled design, and a number of sizes of spiders to accommodate standard sizes of punchings have therefore been developed. In this design, shown in Fig. 53, the punchings are assembled directly in the spider. Air ducts are provided between the shaft and core, between rotor and stator cores, and between stator core and spider. Baffles are arranged so as to force the air through the windings and core in the most efficient manner, and a damper is provided in the base of the regulator to control or shut off the air.

Laminations

The laminations for the cores are punched from high grade silicon steel to insure the lowest possible energy loss. For all standard single-phase regulators, the laminations

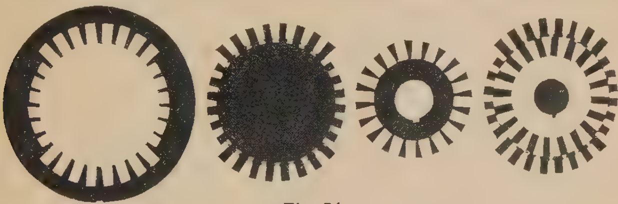


Fig. 54
Punchings of Single-Phase Regulator

for both the primary and secondary cores are punched out of a single sheet, as shown in Fig. 54. This figure shows: first, the secondary punching; second, the inside from the secondary; third, the primary punching made from the inside of the secondary; and fourth, the scrap from the primary and secondary slots held together by the scrap from the air gap. The air gap in this case is 0.040 inches on a side.

The dies to produce such punchings must be kept in the best of condition. Their proper care insures a minimum burring of the laminations during the punching operations and hence a minimum short-circuiting of the laminations which short-circuiting increases the eddy current losses.

The laminations for polyphase machines are similarly made but the winding slots are notched out with an index die. All slots in the rotor are of one size. This also is true of the stator slots, but the rotor slots and stator slots are not necessarily duplicates.

After the laminations are annealed and insulated they are assembled in the tank or spider, or on the shaft. As they are being assembled, they are subjected at regular

intervals to a pressure of about 250 lb. per sq. in. to insure a rigid solid core. The locking (or holding) keys, pins or nuts are secured in place while the laminations are under pressure.

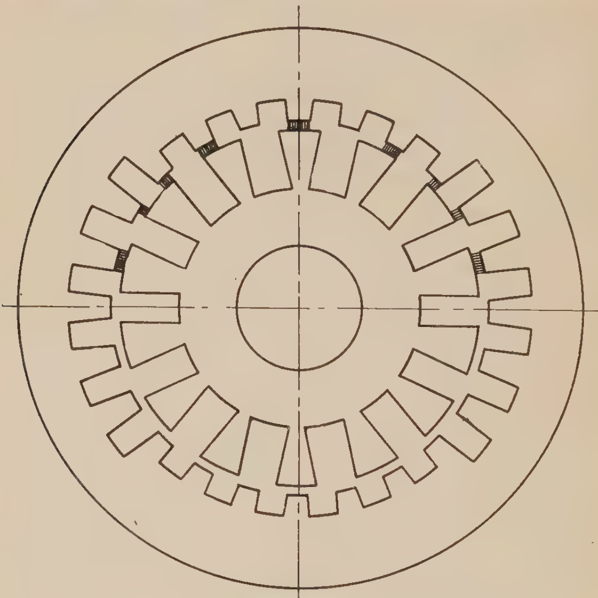


Fig. 55
Ideal Ratio of Widths of Slots and Teeth (Shaded Portion per Pole is Constant Regardless of Position of Rotor)

In determining the width of slots and teeth of the rotor and stator so as to obtain as nearly as possible a uniform air gap, the requirement is that the summation of the shaded portions of the air gap per pole (Fig. 55) be constant regardless of the position of the armature.

Shaft

The shaft on which the rotor is mounted is extremely heavy; for all standard sizes of machines, it is practically one-third of the diameter of the rotor. It is designed to

have its maximum strength at the point of greatest stress. This is between the armature and the top-bearing. A high grade of stock is used to insure further strength and rigidity. To prevent vibration, the bearing clearances are small—approximately 0.0005 inches per inch diameter of shaft. For this reason, the bearing surfaces of the shaft are ground after the core is assembled.

The top end of the shaft is drilled and tapped, and is provided with an eyebolt by means of which the armature can be handled. This eyebolt should not be used to lift the entire regulator.

Noise

Considerable emphasis has been laid on the use of rigid parts in order to eliminate vibration. The tendency to vibrate is inherent in the design, and is due to the stationary position of the armature. At no load, but under excitation, the armature is in a state of stress unless the air gap between the rotor and stator is absolutely uniform. This condition cannot be obtained in the ordinary process of manufacture. An unequal air gap distorts the magnetic field, for the density is highest in that portion of the air gap which is shortest, and as the magnetic pull is proportional to the square of the flux density, an unequal gap produces an unequal pull. Unless the mechanical parts are sufficiently rigid, this unequal pull flexes the shaft and spider and thus further increases the inequality in the magnetic density. This further increases the pull which may become sufficient to pull the rotor and stator cores into contact at one side. As the flux is an alternating or rotating one, varying from a maximum to zero in the single-phase type and rotating in the polyphase type of regulator, an unequal air gap tends to cause the regulator to vibrate with the frequency of the circuit from which it is excited, and

unless the parts are sufficiently rigid and properly designed, noisy operation of the regulator results.

In the same way that an unequal air gap causes lateral vibration, so will an improper arrangement of teeth and slots cause a rotary vibration. As the ideal proportions in the widths of the slots and teeth cannot always be exactly obtained because of other requirements of design, the vibration must be mechanically limited to such an extent as to be unobjectionable. A similar condition prevails under load, and is aggravated by the distortion of the flux by the load and by the power-factor of the load as indicated in Figs. 40 to 43 inclusive. A single-phase regulator has, in general, a greater tendency to vibrate than a polyphase machine, and any regulator which is perfectly satisfactory on a high power-factor load may become noisy as the power-factor of the load decreases.

As the parts tend to vibrate with the frequency of the circuit, it is important that the natural period of vibration of the rotor and stator do not coincide with this frequency. The common frequencies of commercial circuits are fortunately limited to 25, 40, 50 and 60 cycles per second. Hence, it is theoretically possible to design both rotor and stator so that their natural periods of vibration will not coincide with these figures although, sometimes, there is not much margin. The variations in materials and the changes in the internal stresses due to machining will, however, occasionally upset all precautions and it is sometimes impossible to eliminate entirely a more or less noisy operation. Furthermore, as materials may change their shape somewhat after machining, especially if subjected to vibration, a regulator originally quiet may in time become noisy. When this occurs, the regulator usually becomes rapidly worse, and the only remedy is to re-center the cores by machining.

Windings

The design of the windings has been indicated to some extent in the previous section. With the exception of the short-circuited windings in single-phase machines, which

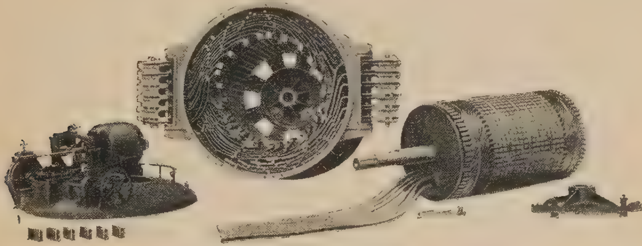


Fig. 56
Six-Phase Air-Cooled Regulator

windings are wound directly in the rotor slots, all windings for all standard regulators are form wound. The design of the coils and their assembly on the core is clearly shown in Figs. 24 to 28 inclusive. Regulators for large current capacities may require specially designed windings and special arrangement of the leads. The series windings for such machines are usually arranged with one conductor per slot, and conditions may require the parallel connection of poles or even the parallel connection of some of the windings of each pole. For low frequencies, the conductors for such regulators can be built up of laminated copper, but for the higher commercial frequencies, stranded cable is required because of the eddy current losses in the conductor itself.

Fig. 56 shows the design of a 25-cycle six-phase regulator in which the secondary current per phase is 4500 amperes. The number of turns per phase in series with the line is one, and all four poles are connected in

multiple. In such cases, it is necessary so to design and arrange the parallel conductors per phase that all sections have the same resistance and reactance so as to insure a uniform distribution of the load, uniform temperature, and noiseless operation.

High-Current Regulators

The regulator shown in Fig. 56 illustrates one of the difficulties in the design of high-current machines. The required ratio of turns as well as the required ratio of slots, must be satisfied by the design. All poles and phases must be identical and the regulator must have a reasonable magnetizing current and impedance. The number of series turns is small and the total cross section of the copper is large. The ampere-turns per slot are limited by the impedance voltage drop and by the heating of the conductor. Hence, to obtain a sufficient copper section, there is sometimes no choice except that of increasing the number of poles for multiple connection. This increase in the number of poles results in an increase in the diameter, weight, and cost.

Winding Supports

All regulator coils are designed to fit tight in the slots, and an allowance of only about 0.0005 inch is made for clearance. After assembling, the coils are securely braced, not only to prevent vibration, but also to prevent distortion during line short circuits. This bracing and the supporting of the coils for the standard single-phase regulator is shown in Fig. 26 in which both the primary and secondary or series coils are similarly corded. The shunt windings of the polyphase regulators are banded as shown in Fig. 28, and the series windings are supported by insulated rings which surround the end portion of coils as shown in the same illustra-

tion. The coils are held in the slot portion of the rotor by binding wire, and in the stator, by wooden wedges as shown.

Leads

As the secondary winding of the regulator is connected in series with the line, it is necessary to bring out both ends of each phase and to provide suitable terminals. These leads and terminals usually have ten times the current-carrying capacity of those required for the primary, but, as the series winding is always assembled in the stator, no particular difficulties are encountered by this requirement. As shown in Fig. 45, these leads are brought out through the side of the secondary spider or tank whenever the punchings are assembled directly in it. When the punchings are assembled in skeleton spiders, the leads are brought out through the cover as shown in Fig. 46.

Both ends of the phase windings of the primaries of single-phase and quarter-phase machines are brought out, but only three leads are brought out of three-phase machines. Either three or six leads are brought out of six-phase machines, depending upon whether they are excited three-phase or six-phase. The primary leads always consist of extra flexible cable and are loosely wound around the shaft as shown in Fig. 44. They are securely corded to the shaft, and in case of regulators of the larger current capacities, are supported so as to avoid any interference with the winding. All leads for both primary and secondary windings are provided with terminals.

The insulating bushing in the spider of the cast iron tank is split and is used as a clamp so that the slack in the cable leads will not be changed after the regulator is assembled. In the skeleton type of regulator, separate clamps, bolted to the spider, are used.

Oil Stops

In all oil-immersed regulators, it is necessary to provide oil stops in the cables at a point above the oil level. A great deal of work has been done in attempting to obtain a stop that will not leak or siphon oil. The cable, as already

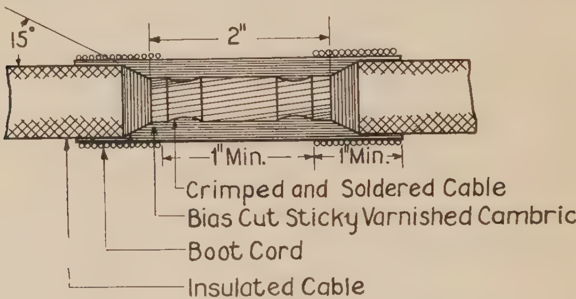


Fig. 57
Varnished Cambric Insulated Oil Stop

stated, is stranded and the insulation on the cable consists of varnished tape. The spaces between the strands of the cable, between the cable and the insulation, and between the layers of the insulation draw up the oil by capillary attraction. As soon as the oil in the cable outside the regulator is below the oil level in the regulator, siphoning action is added to the capillary action, and oil leakage results.

Judging from experience, it is practically impossible to provide an absolutely oilproof joint except by using a solid bare conductor. The use of such a conductor is impracticable because of the voltage between leads and to ground and the flexibility required. The oil stop so far giving the most satisfaction is shown in Fig. 57. The cable is first crimped in a die with double jaws, and while under pressure, the section between the jaws is filled with solder. After cooling, this section is smoothed off, taped with bias-cut

tape and finished with cording. The cable and both sides of the tape are well covered with heavy varnish or shellac. This stop will give satisfactory results if well made.

Gearing

As previously stated, the armature of an induction regulator under excitation and load tends to rotate, except in certain positions. Under excitation only, this tendency is due to the tooth torque and is present only in case the air gap density is not uniform because of the design of the teeth. Under load, it is due to the reaction between the ampere-turns of the rotor and stator. The torque due to the latter action is, in a polyphase regulator, equal to that of an induction motor of the same kv-a. capacity, and it is therefore necessary to provide gearing to rotate the armature against this torque. The gearing must also be self-locking, and for this reason it is necessary to use a worm and gear.

This gearing must be exceedingly strong and heavy to withstand the regulator torque due to line short circuits and must have a high ratio so that the regulator can be adjusted under load. The worms are made of steel and are provided with thrust ball bearings. The gear segments are made of a high-grade bronze. For the smaller regulators, the segments are made of a single bronze casting; but, for the larger machines, the hub and the web or arms are made of cast steel and only the rim containing the teeth is of bronze. This gearing is very inefficient; first, because of the slow speed of operation; second, because of the necessity of having to be self-locking; and, third, because of the large ratio of reduction required.

Gearing Efficiency

Worm gearing has a maximum efficiency when the teeth on the worm are cut at an angle of from 30 to 70

degrees with the axis. Such angles are prohibitive for regulator gearing because the gearing would not be self-locking. The tooth angle at which a uniform and steady torque of the worm gear segment will turn the worm is

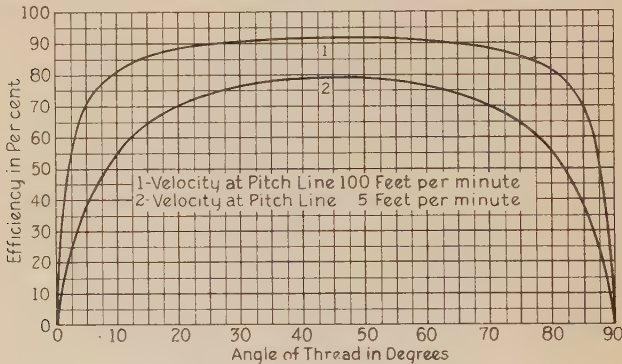


Fig. 58

Relation Between Thread Angle, Speed and Efficiency of Worm Gears

about 10 degrees, but due to the vibration of the regulator armature, this angle must, in the present application, be reduced to from 3 to 4 degrees in order to insure locking. At this angle, the gearing efficiency is exceedingly low.

All regulators up to about 400 kv-a. are operated by means of a single worm and gear, but those of larger capacity require a double reduction in order to permit their adjustment by hand. With the double worm reduction, it is advisable to cut the main worm, which operates at low speed, with a double or triple thread. This increases the thread angle and increases the efficiency. It is then necessary to provide the motor shaft which operates at a high speed with a worm having a small angle of thread. This worm is depended on for the locking effect, but a fair efficiency is obtained due to the speed at which this worm operates. As a matter of interest, Fig. 58, is given. This

illustration shows the efficiency of worm gearing with relation to the angle of thread and speed of operation.

Practically all regulators are operated by a motor mounted on the regulator cover. The motor is of special design in that it has an exceedingly high starting torque. Provision also is made, however, for hand operation by means of a handwheel mounted on the worm shaft.

Fig. 59
Single-Phase Regulator Armature and Cover Removed from Tank

Disassembly of Regulator

As shown in Figs. 46 and 59, regulators are readily disassembled for inspection. A complete disassembly of the cast iron tank design is shown in Fig. 60 and that of the skeleton frame type in Fig. 61. From these illustrations, it is apparent that there is little choice between the two designs with regard to accessibility and to facility for making repairs. The rotors may be removed in either case without drawing the oil out of the tank, and while in the skeleton construction the stator may also be so removed, the amount of oil in the cast iron tanks, which are used only for the small sizes of regulators, is so small that no difficulty should be experienced in its care until the regulator is again assembled.

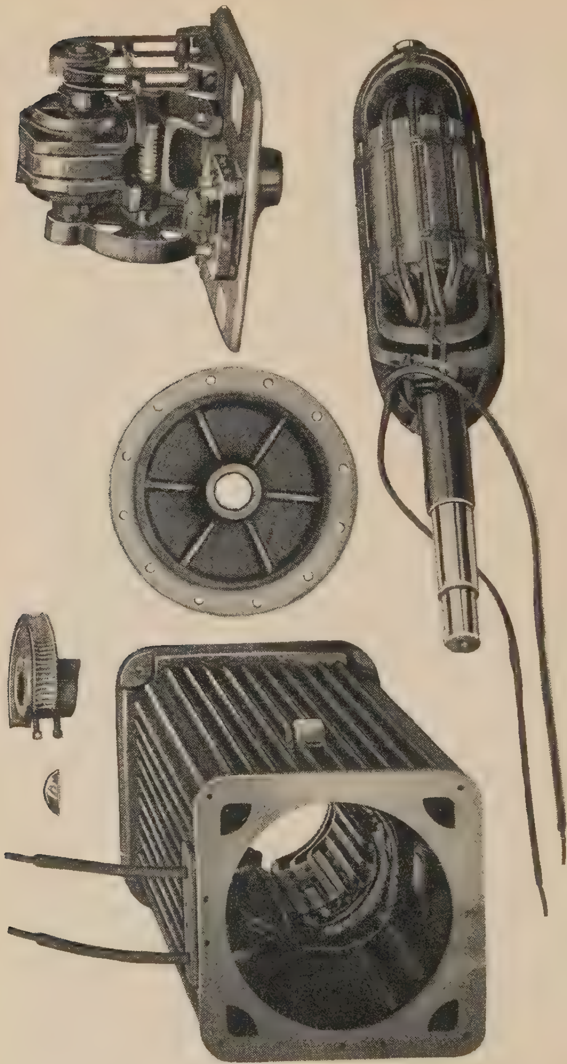


Fig. 60
Disassembled Single-Phase Regulator

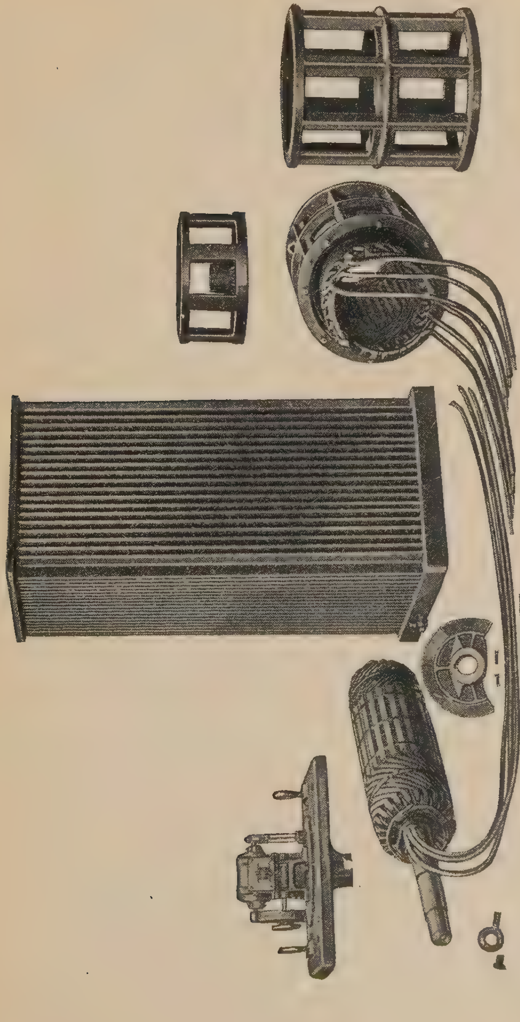


Fig. 61
Disassembled Three-Phase Oil-Immersed Self-Cooled Regulator

SECTION VIII

OPERATING MECHANISM

Induction regulators may be adjusted either by hand or by motor. The mechanism of a hand-operated regulator consists of a worm and worm gear segment. The handwheel for adjusting is mounted either directly on the worm shaft or is geared to it by a further reduction gearing.

Ratio of Gearing

In addition to being self-locking, the gearing ratio must be such that the torque of the regulator can be overcome manually by means of the handwheel. This ratio is obtained by selecting worm gears of proper diameter. The selection is, however, limited by the size of the regulator cover and the pitch of the worm teeth. The size and strength of the teeth are determined by the torque of the regulator. Where a single gear of proper size cannot be accommodated on the cover, as in the case of large regulators, the ratio of gearing is obtained by a combination of worm gearing and spur gearing, or by a double reduction worm gearing.

The direction of rotation of the regulator armature to lower the line voltage is generally right-handed or clockwise. This is also the direction of rotation for the handwheel. The worm gearing is right-handed or left-handed so as to satisfy this requirement.

Whether the regulator is hand- or motor-operated, stops are provided on the cover to prevent the worm gear from being turned out of mesh with the worm.

The majority of regulators are adjusted by means of small polyphase motors, and in such regulators, the mechanism consists of a worm and segment, operating motor,

brake, and limit switch. The brake operates on the motor shaft and is adjusted so as to prevent an overtravel of the regulator due to the inertia of the operating motor armature. The limit switch is in series with the control or relay switch, and is arranged and connected so as to open the motor circuit as soon as the regulator has reached either extreme position. It, however, again automatically closes this circuit as soon as the regulator armature recedes from the extreme position. The opening of the switch does not interfere with the movement of the regulator in the opposite direction.

All two-pole motor-operated regulators of General Electric Company design are adjusted through a single worm and segment, and spur gearing. The motor shaft is provided with a permanent brake. Four-pole regulators are arranged with a double worm reduction gearing, and in them, the brake on the motor shaft is of the magnetic type.

Since the torque of a regulator is inversely proportional to the speed of rotation which the armature would obtain if it were free, for any kv-a. capacity a two-pole regulator has one-half the torque of a four-pole machine. Consequently, the four-pole regulator requires gearing of twice the strength, and this requirement always demands, for the larger sizes of regulators, the use of the double reduction worm gearing.

The ratio of the gearing between the operating motor and the regulator is also determined by the time allowable for the voltage adjustment, and by the initial and maintenance costs of the operating mechanism. An instantaneous voltage adjustment would be the ideal condition, but since the armature of the regulator has considerable inertia even at its slow speed of rotation and the armature of the operating motor has a considerably higher inertia

because of its higher speed, an appreciable amount of time and power is required to start, as well as to stop, the movement of the parts. The starting is obtained by the motor

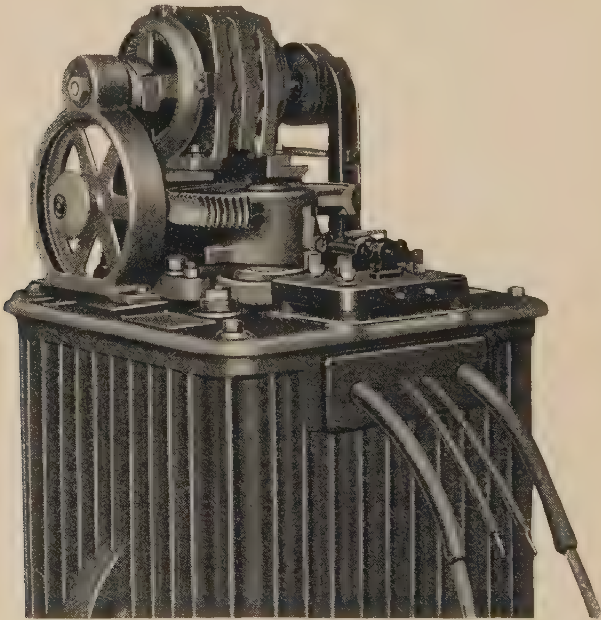


Fig. 62
Mechanism on Single-Phase Regulator

torque, and the stopping is accomplished by the motor brake.

The higher the speed of the regulator, the larger must be the motor and mechanism, and the greater will be the wear and hence the upkeep required. As a consequence, both the initial and maintenance costs will be increased. Regulators having capacities up to approximately 50 kv-a. require about 10 seconds to operate from maximum boost

to maximum lower, whereas a regulator rated 1000 kv-a. requires about 40 seconds. This arrangement is generally satisfactory, however, for the smaller regulators are used

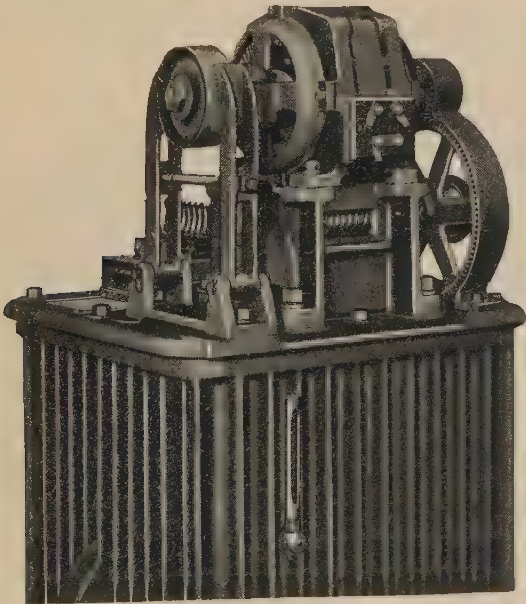


Fig. 63
Mechanism on Single-Phase Regulator—(Rear View)

for the control of lighting circuits, while the larger sizes are generally limited to power circuits. Figs. 62 and 63 show the mechanism of the two-pole regulator, and Fig. 64 shows that of the four-pole design.

Mechanism for Two-Pole Regulators

In the two-pole design, all surfaces on the cover which are used for the mounting of the mechanism are preferably in one plane. The motor is mounted on a separate support which contains the worm gear with its thrust ball bearings,

its shaft and shaft bearings. This arrangement facilitates accurate machining and adjustment between worm and gear. After adjustment, the motor support is fixed in place

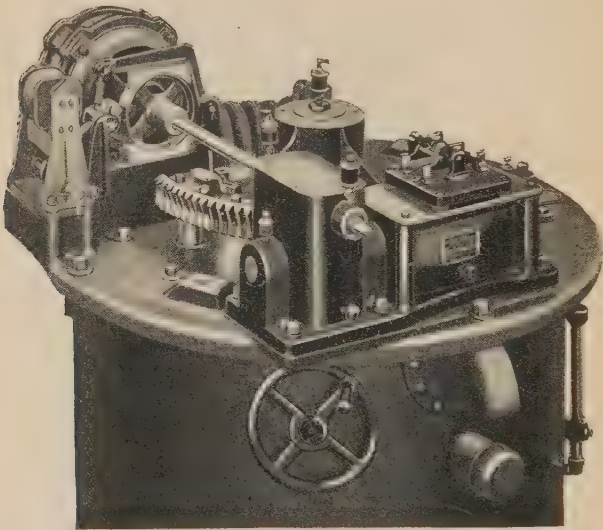


Fig. 64
Top of Three-Phase Oil-Immersed Forced-Oil Regulator

by two dowels. Oil cups with wick oilers are provided for the worm shaft bearings and an oil well is provided for the worm. This arrangement insures lubrication with a minimum of attention.

The segment is provided with stops which trip a limit switch at the extreme positions of the regulator. These stops are additional to the mechanical stops previously mentioned.

Motor Brake

The brake, which is leather lined and adjustable, somewhat increases the power required of the operating

motor. The operating motor required for the two-pole design of regulator is, however, comparatively small. All standard regulators are operated by fractional horse power slow-speed motors and the over-running of the motor armature can readily be taken care of by this type of brake. The brake pressure required is comparatively light, and because of the relatively large

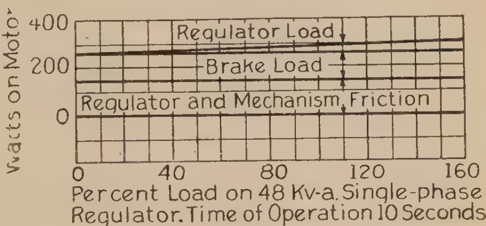


Fig. 65
Regulator Motor Operating Duty

magnetizing current of small motors, the current taken by the motor is not appreciably increased due to the brake load. For instance, with full voltage applied to a 220-volt three-phase operating motor for a 48 kv-a. single-phase regulator, the no-load current with the motor running free is about 1.8 amperes, whereas the motor current with full load on the regulator is only about 1.9 amperes.

Fig. 65 gives the power required by a motor to operate a 48 kv-a. single-phase regulator. The power consumed by the brake may seem large in proportion to the total but a magnetic brake would also consume power and its magnetizing current would be added to the motor current. This would increase the current carried by the relay switch and cause increased burning of the contacts. With the permanent brake, the current carried by the relay switch is therefore less, and consequently the wear of the contacts is less. The permanent brake is, moreover, of such simple design that for it to get out of order is practically

impossible. This brake simplifies the installation, increases the life of the mechanism, is absolutely noiseless, and absolutely satisfactory in every way.

Figs. 62 and 63 show the mechanism of a standard single-phase 48 kv-a. regulator. The worm is cut with a single thread (three per inch) and has an outside diameter of 2.25 inches. The ratio of the worm gearing is 86, that of the spur gearing 3.5; hence, the total ratio between motor and regulator is 301. The motor has a starting torque of 5 ft-lb. and a speed of 1200 r.p.m., so that the regulator, being two-pole, requires about 8 seconds for its total range.

As standard regulators are usually designed for 10 per cent boost or lower, the average speed of adjustment is therefore about 2½ per cent voltage change per second. Due to the characteristics of the boost and lower curve (Fig. 6), the rate of change in the neutral position of the regulator is, however, twice as great (that is, about 5 per cent voltage change per second). If the line voltage is maintained within 1 per cent of normal, the motor must therefore be brought to rest, even from full speed, in the equivalent of one-fifth second. In other words, a 1200 r.p.m. motor must be brought to rest from full speed within four revolutions of the motor armature. In dealing with fractional horse power motors of low speed, this involves no particular difficulty. With the brake surface lubricated and a motor of the design shown, the brake pressure required is only 5 lb. The brake pulley is 4.5 inches in diameter.

Exceedingly rigid and substantial spur gearing is used so as to withstand the shock of starting and stopping. The pinion on the motor is a fabroil gear and is not only well adapted to withstand this kind of service but is also absolutely noiseless. The gearing is enclosed in a casing as shown in the illustrations.

Mechanism for Four-Pole Regulators

As previously stated, the torque of the four-pole regulator is twice that of the two-pole regulator having the same kv-a. rating. Consequently, the gearing for the former must be twice as strong as that for the latter, and to operate the regulator with the same size of motor will require twice the ratio of gearing. This gearing ratio will give the same time of operation for the four-pole as for the two-pole regulator because the former rotates through an angle of 90 degrees whereas the latter rotates through an angle of 180 degrees.

The use of the four-pole design is confined to regulators of large kv-a. capacities, and they are usually artificially cooled. Hence, their mechanical dimensions are comparatively less than those of the two-pole design and comparatively less space is available on the regulator cover to accommodate the operating mechanism.

It would be desirable to maintain the same speed of operation in the larger sizes of regulators as in the smaller units. This would, however, require an increase in the size of the operating motor proportional to the increase in the rating of the regulator and would result in an increase in its cost. To design a brake to stop so large a motor in a sufficiently short time to prevent hunting would also increase the initial cost as well as the cost of upkeep. However, as the larger regulators are generally used on power systems, it is not essential that they operate so quickly as those used on lighting feeders. In order, therefore, to meet the mechanical design limitations and maintain a reasonable cost, they are designed for lower speeds.

A double reduction worm gearing is more suitable to meet the conditions of limited space and a high ratio of

speed reduction than the combination of worm and spur gearing used on the smaller regulators. This arrangement is illustrated in Fig. 64. The gearing is exceptionally heavy and is provided with ball thrust bearings. The motor brake is of the magnetic type. As previously indicated, the power taken by the permanent brake is a relatively large percentage of that delivered by the motor. This is of no particular consequence when dealing with fractional horse power motors but must be taken into account when considering motors of larger sizes such as are used on four-pole regulators. The magnetic brake used is of the toggle type and is adjustable. This arrangement gives the maximum brake effort for a minimum expenditure of energy and current. This brake is shown in Fig. 64. It is substantial in construction and requires no attention other than an occasional adjustment to take up the wear of the brake shoes.

Fig. 64 shows the mechanism for a 1000 kv-a. 60-cycle regulator. The main worm is cut with a double thread (one thread per inch) and has an outside diameter of 5.125 inches. With the dimensions given, the tooth, at the root, is 0.69 inch thick. The ratio of this gearing is 56. The motor worm has an outside diameter of 3 inches and is cut with a single thread having 1.6 threads per inch. The ratio is 40 and consequently the ratio between motor and regulator is 2240. The normal torque of the regulator at full load is practically 4000 ft-lb. and at 50 per cent overload, 6000 ft-lb. The starting torque of the motor at full voltage is 110 ft-lb., and at 80 per cent voltage, approximately 70 ft-lb. The motor torque required to overcome the static friction of the regulator at no load is 30 ft-lb. With 80 per cent voltage on the motor, this still leaves 40 ft-lb. available to overcome the regulator torque. As

the regulator torque is 6000 and the gearing ratio 2240, the torque required by the motor is theoretically 2.68 ft-lb. With the motor torque available, an allowance is therefore made for a gearing efficiency of about 6.7 per cent. In practice this allowance has been found to be that which may be required if the lubrication of the gearing is neglected or the ball thrust bearings should become much worn. With good lubrication and the highest grade of thrust ball bearings for both worms, the efficiency of this gearing, when operated by a 900 r.p.m. motor, is about 16 per cent. This efficiency is about one-half that obtainable with the single reduction worm gearing used on the two-pole design of regulators, and is one reason for using the magnetic type of brake on the larger regulators.

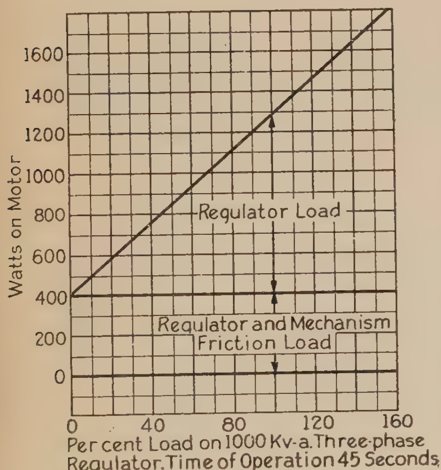


Fig. 66
Regulator Motor Operating Duty
(Running Condition)

The efficiency of each worm used in the double reduction is considerably in excess of that of the worm used in the single reduction. The reasons for this are: first, the motor worm is operated at higher speed; and, second, the thread angle of the main worm is greater than that applicable with the single reduction. The total efficiency is, however, the product of the efficiencies of the two worms

which, as stated, is about one-half that of the worm used in the single reduction gearing. The operating characteristics of the mechanism of the 1000 kv-a. regulator shown in Fig. 64 is illustrated in Fig. 66.

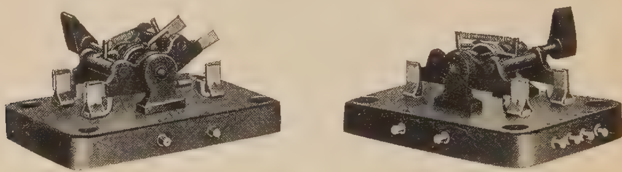


Fig. 67
Limit Switch for Induction Voltage Regulator

The preceding consideration of the design and requirements of the operating mechanism emphasizes the fact that the service required of both the motor and brake is particularly severe, especially during the period when the motor is being brought to rest since this must be accomplished in an exceedingly short interval of time; in some designs, within only a few revolutions of the motor armature. It obviously is impractical to stop the motor instantaneously because of the racking effect on both the motor and brake. For this reason, provision for a time allowance is made in the automatic control of the regulator. By the proper adjustment of this control, as well as by a corresponding adjustment of the brake pressure, the regulator is brought to rest as soon as the proper adjustment or correction of voltage has been accomplished.

A brake release is provided on all types of regulators so that the adjustment can more readily be accomplished by hand.

Handwheels

The handwheel of all two-pole regulators is mounted on the worm shaft. In the larger sizes of the four-pole

design of regulators, the handwheel is mounted on the motor shaft. As the handwheel is seldom used, and as its removal reduces the work of the brake, the handwheel on the larger sizes of regulators is not permanently mounted but is so arranged that it can readily be slipped on the operating shaft whenever hand adjustment of the voltage becomes necessary. A hook for the handwheel is provided on the regulator cover immediately below the operating shaft. When the handwheel is not used for adjusting the regulator, it should be placed on this support.

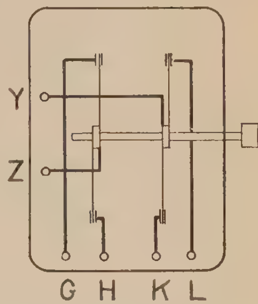


Fig. 68
Connections of Limit Switch

Limit Switch

The limit switch is shown in Fig. 67 and its diagram of connections is given in Fig. 68. The switch is made double-pole double-throw, is of the quick-break design, and is self-closing. It is mounted directly on the regulator cover or on the motor support and is so arranged that, as the regulator segment reaches either end of its travel, one side of the switch is tripped by means of adjustable tripping lugs on the worm gear segment. This cuts the motor out of circuit. However, as previously stated, this does not interfere with the operation of the motor in the opposite direction.

As the regulator segment recedes from either maximum position, it allows closure of that side of the switch which was tripped, but the closing of the switch is gradual. Were the two stationary contacts of the same length and the regulator stopped just as one blade came into contact with its stationary contact, and if the relay switch were reversed,

then the motor would be connected to the line single-phase and would probably burn out. To avoid this danger, one stationary contact on each side of the limit switch is purposely made shorter than the other. The relay switch magnet is then connected in series with this short contact. Thus, the relay switch cannot close and cannot connect the motor to the line unless both sides of the limit switch are fully closed.

The two-pole switch shown is used whether the operating motor be single-phase, two-phase, or three-phase. When used with two-phase motors, two of the motor leads are connected directly to the source of supply, and when used with a three-phase motor, the third motor phase is so connected.

Alarm Signal

The limit switch may readily be arranged with additional contacts which are closed when the motor circuit is open so as to indicate to the operator, either by a signal lamp or an alarm, that the regulator has reached its limit of travel.

The operating mechanism, whether for the two-pole or four-pole regulator, is designed to withstand any reasonable overload to which regulators are sometimes subjected due to line troubles. It is accessible, can be readily disassembled if disassembly should become necessary, and is protected by a housing which protects both the mechanism and the operator. The lubricating facilities are such that the mechanism requires a minimum of attention. The mechanism is noiseless in operation and has given general satisfaction.

SECTION IX

THE OPERATING MOTOR

The operating motor for the standard design of induction regulator is at rest as long as the voltage of the regulated feeder is within the predetermined limits, and it is started only when the voltage varies from normal.

As the static friction of the regulator and mechanism is considerably greater than the running friction, the maximum effort of the motor is required at starting. Theoretically, the motor should therefore be designed to give its maximum torque at zero speed.

Voltage conditions on mixed lighting and power circuits occasionally demand regulator adjustments at the rate of 40 times a minute for long periods of time. In order to satisfy this requirement, the motor must start and attain speed as quickly as possible. Then, as soon as the voltage is adjusted, it must as quickly be stopped so as to prevent hunting. The former requirement of the motor is obtained by a design which gives the maximum torque at zero speed, but the latter requirement must be obtained by means of the brake. Under rapidly fluctuating line voltage conditions, the motor may also require reversal under full speed. This greatly increases the requirements regarding the design of the motor.

In dealing with fractional horse power motors, a high speed of operation involves no particular difficulties in the design of either the motor or the brake; but, as the inertia of the motor armature as well as that of all rotating parts is proportional to the square of the diameter and varies directly with the weight, such a short time of operation is impracticable for large regulators operated by the larger motors. The standard 48 kv-a. single-phase regulator, for instance, is operated by a motor equivalent in size to a standard ¼ h.p. machine, whereas a 1000 kv-a. three-phase

regulator is operated by a motor equivalent in size to a standard 15 h.p. machine. To obtain as high a rate of speed for the larger regulators as for the standard lighting sizes, abnormally heavy mechanism would be required, and the upkeep and cost would be prohibitive.

The general requirement of all operating motors, however, demands a construction which is exceedingly rigid and substantial, and of liberal design.

Current and Voltage Limits

With frequent operations, the relay switch which controls the motor may make and break the starting current almost continually. It is therefore highly desirable to limit the motor-starting current to as low a value as possible. For this reason, it is advisable to wind the motors for the larger sizes of regulators for 220 volts. For reasons of design and safety, the motor voltage should not exceed 250 volts.

The relay switch is two-pole double-throw, and controls only two phases. The third line phase is connected directly to the motor. Due to any unequal wear of the switch contacts, to improper adjustment, or to failure, only one switch phase may be closed and a single-phase connection be so obtained. With this connection, the motor will not start and the connected phase will carry full starting current until the circuit is again opened by the relay switch. The operation of the switch, however, depends on the fluctuations in the line voltage rather than on the voltage adjustments of the regulator. Because of this possibility of a single-phase connection and also because of the frequent starting and reversal of the motor at full speed, the motor winding should be designed with a large margin of safety.

Design

Motors used to operate General Electric Company regulators are especially designed throughout for this class of service, and they meet all of the requirements. Fig. 69 shows a typical torque and current characteristic; Fig. 70 shows a motor complete; and Fig. 71 shows a motor disassembled. The motors are self-oiling and well ventilated. The motor shaft is made exceptionally heavy in order to withstand the torque strains, especially during reversal at full speed. The shaft ends are tapered and keyed for the brake pulley and pinion which are held in place by keys, nuts and lock washers. Fabroil pinions are used, and they insure long life and absolutely noiseless operation.

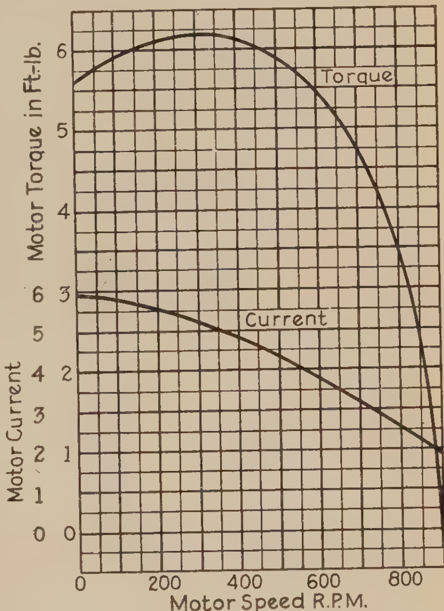


Fig. 69
Operating Characteristics of Regulator-Operating Motors

Fig. 69 which shows the torque curve, indicates that the maximum torque is not obtained at zero speed. As indicated by this curve, the design of the motor is such that a torque equivalent to the required starting torque is

maintained over a considerable range of speed. This is done in order to avoid sacrificing speed in the adjustment of the line voltage for the starting requirement, although the friction of the regulator mechanism is greatly reduced

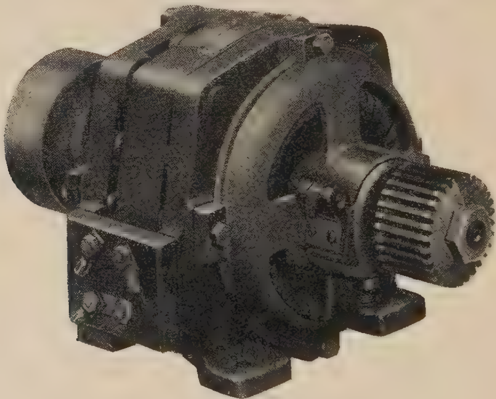


Fig. 70
Regulator-Operating Motor

after the regulator is once started. The torque curve of a motor having the maximum torque at zero speed drops very rapidly, whereas, with the design used, the motor operates at nearly full speed with full load on the regulator.

The current curve shown in Fig. 69 is also characteristic for all regulator-operating motors. The starting current compared with the running current is very much less than in motors of standard design.

By limiting the starting current as shown, the duty of the control or relay switch is greatly reduced and the motor windings can more readily be arranged to carry the starting current for extended periods as may occasionally be required.

In distributing stations containing a number of feeder regulators, it is the usual practice to operate the regulator

motors and the control switches from a common bus rather than from the feeder controlled. If operated from the feeder, the voltage on the motor is subject to the feeder voltage variations, and the feeder voltage may be high or

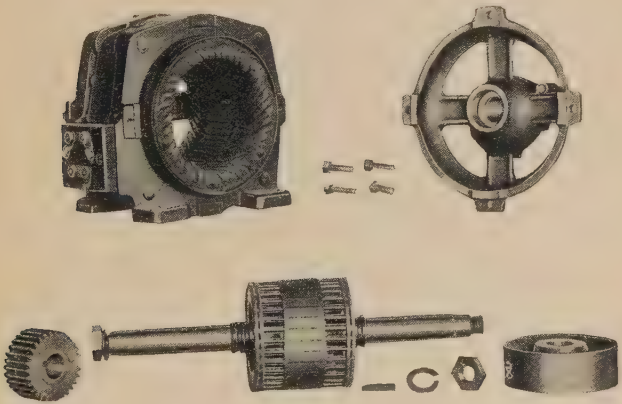


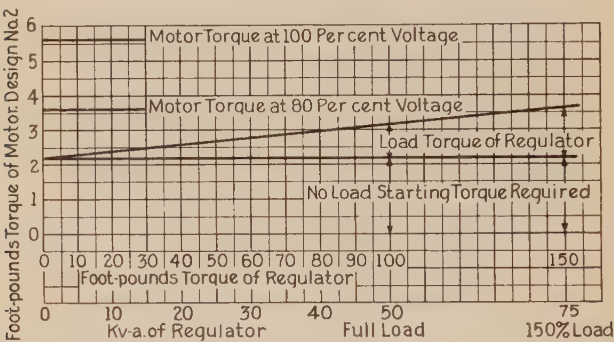
Fig. 71
Disassembled Regulator-Operating Motor

low, depending upon the regulation requirements. As the motors must operate the regulators under any voltage condition, they are so designed that at 80 per cent of their normal rated voltage they are able to operate the regulators in either direction when the regulators are carrying 150 per cent load.

The design is made sufficiently liberal so that the motors will not be injured in case of an occasional and intermittent single-phase connection due to an improper operation of the relay switch. In order to reduce the brake effect to a minimum, the motors are designed for as low a speed as practical; the standard 60-cycle speed being 1200 r.p.m. for all sizes.

Operating Requirements

A number of standard sizes of operating motors have been developed, and the various sizes of regulator covers have been adapted for their mounting. In thus combining



Gearing Design No. 2	
Worm Gear Ratio	86
Spur Gear Ratio	3.5
Total Ratio	301

Regulator Requires 3.6 Ft-lb. on Motor Shaft at 150 Per Cent Load

Motor Gives 3.6 Ft-lb. at 80 Per Cent Voltage

Fig. 72

Characteristics of Operating Motor and Mechanism for 50 Kv-a., 60-Cycle, Two-Pole, Three-Phase Regulators

operating motors and regulators, the requirements are always pre-established as illustrated in Fig. 72, and a motor of such size as will fully meet every requirement is selected. In the smaller sizes of regulator, one size of motor is used with a given set of regulator parts regardless of the kv-a. capacity of the regulators assembled in them because the friction of the regulator and brake, rather than the regulator torque, determines the requirements. In the larger sizes of regulators in which the regulator torque predominates, a single cover may be adapted for two or three sizes of motors, as, for instance, motors for single-phase regulators, for the self-cooled polyphase type, and

for the artificially cooled polyphase type, any one of which may be assembled in a given set of regulator parts but which require motors of different characteristics.

Due to the severe service requirements, operating motors used with induction regulators should be of the polyphase squirrel cage type. Such motors minimize the possibilities of trouble and eliminate the necessity of attention required by the brush rigging or clutches used in motors of other designs. If, however, no polyphase power is available, single-phase motors having the same general design and operating characteristics can be furnished, but they will necessarily require some attention, depending on the severity of the service demands.

SECTION X

METHODS OF COOLING REGULATORS

The dissipation of the heat generated in the windings is the principal limiting feature in determining the kv-a. output which can be obtained from a regulator of any given mechanical size. The transfer of this heat out of the regulator depends: upon the cross section of the winding per coil and slot, upon the insulation on and between the individual conductors composing the coil, upon the insulation on the outside of the coil, upon the percentage of the coil embedded in the sheet iron core, upon the spacing between the coils, and upon the method of conducting the heat from the coils out of the regulator.

All materials present a resistance to the flow or transfer of heat. This resistance differs for different materials, is uniform for any given material, and is greatly increased by a junction of two materials due to the imperfect contact between them.

Regulators are either self-cooled or artificially cooled. A self-cooled regulator may be assembled in an open frame or it may be assembled in an oil container filled with oil.

In the former design, the cooling of the regulator depends on the circulation of the air through and around the windings and cores. In the latter design, it depends on the transfer of the heat from both coils and cores to the oil, from the oil to and through the tank, and from the tank to the surrounding air. The tank is usually arranged with projections in order to increase its radiating surface so as to facilitate the transfer of the heat.

Artificially cooled regulators may be of the air-blast design or of the oil-immersed design. In the air-blast design, a flow of air is forced through the windings and cores. In the oil-immersed design, the oil may be circulated

artificially and cooled by forcing it through a radiator or other cooling medium, or a cooling coil may be placed directly in the regulator tank and water circulated through this coil for the purpose of cooling the oil.

In all except the forced-air and forced-oil designs, the circulation of the cooling medium is due entirely to the difference in the specific weight of the hot and cold cooling medium surrounding the regulator core and windings. The heated air or oil rises to the top and is replaced by the cooler medium from the bottom, thus establishing a circulation.

In the oil-immersed regulator, the oil around the coils and cores is heated. The increase in temperature causes it to expand and decrease in specific weight. Then, being lighter than the surrounding cooler oil, it rises to the top of the tank and is replaced by the cooler oil. The continued heating of the oil by the windings and cores causes the oil which flows toward the top of the tank to flow toward the sides and downward. Here the oil is cooled either by contact with the surface of the oil container and its radiators or by passing between the spirals of a water-cooled iron or copper coil. The oil, which is thus cooled, again contracts in volume, increases in specific weight, and flows to the bottom of the tank from which place it is again drawn up into contact with the windings and cores by the upward flow of the heated oil. The process is continuous. The rate of flow depends on the increase in the temperature of the oil in contact with the windings and on the decrease in its temperature due to its contact with the cooling medium, that is, the flow is due to its continuously changing weight per unit of volume.

The building of self-cooled regulators which are not immersed in oil is not practical except in the smaller sizes,

because of the difficulty of obtaining sufficient air circulation around and between the windings. Based on volume, air has a heat storage capacity which is approximately one twenty-fifth that of oil. To remove the same amount of heat, the movement of air must therefore be twenty-five times as fast as if oil were used. Hence, due to the comparatively large volume of air required to absorb the heat loss, the air passages between the cores and coils must be so large that the design becomes prohibitive except for very small regulators.

Furthermore, the heat dissipated by a unit area of surface of the windings may be approximately the same as that transmitted to the air by a unit area of surface of a tank. The tank, however, dissipates this heat by both radiation and convection air currents; whereas the heat from enclosed windings is dissipated almost entirely by convection currents. The heat dissipated from a tank by radiation is approximately one-third—and that dissipated by convection currents is approximately two-thirds—of the total heat given up to the air. The tank is freely exposed to the air and the friction of the air convection currents which are set up is negligible compared with the friction of air passing through windings arranged for air circulation. Restated: because of design limitations, a tank surface is much more efficient in dissipating heat than a coil surface. From this it follows that any self-cooled regulator will operate at a lower temperature if oil-immersed.

For the reasons just given, oil-immersed self-cooled regulators can be built in much larger sizes than regulators of natural draft design.

Temperature versus Insulation

Forcing the cooling medium through the windings greatly facilitates the transfer of the heat by maintaining

a greater difference between the temperatures of the windings and of the cooling medium. Hence, for any given machine, artificial cooling allows a greater output for the same temperature rise both in the windings and in the core. The rate of increase in the kv-a. capacity of the regulator is, however, largely governed by the insulation in and around the windings. Electrical insulation is also heat insulation, and as the amount of insulation depends on the voltage for which a regulator is wound and insulated, it follows that in a low-voltage regulator the increase in the kv-a. capacity resulting from artificial cooling is greater than can be obtained in a high-voltage machine. In other words, the difference between the temperature of a given copper conductor carrying a given current and that of the cooling medium increases with the voltage for which the conductor is insulated.

Disregarding for a moment the temperature drop between copper and insulation and between the insulation and the oil in an oil-immersed regulator, the temperature difference between copper and oil is directly proportional to the thickness of the insulation, and also directly proportional to the heat dissipated from the surface of the insulated coil per unit of area; that is, the temperature difference is proportional to the rate of flow of heat. With a given loss in the copper, any increase in the thickness of the insulation is accompanied by an increase in the temperature drop in the insulation and by an increase in temperature of the copper. With a given thickness of insulation, an increase in the heat loss in the copper results in a greater temperature drop in the insulation, and, hence in hotter copper.

This may be illustrated by the following table which gives only approximations rather than exact data. Assum-

ing first, that the temperature of the entire section of the copper in a coil is uniform, that is, that there is no temperature drop between the center of the coil and its bare surface; second, that there is no temperature drop between copper and insulation, and between insulation and oil; and, third, that the heat dissipated per unit of area of insulation is the same for the four cases considered and that the total amount of heat dissipated remains constant, that is, that for the four thicknesses of insulation compared in the following table, the outside dimensions of the coils are identical; then under these conditions, the following relations are illustrative:

Thickness of insulation........	0.00	0.05	0.10	0.15
Temperature of entering cooling medium in deg. C...........	30	30	30	30
Temperature of outgoing cooling medium in deg. C...........	40	40	40	40
Temperature of copper in deg. C.	40	80	120	160
Temperature of insulation at surface in deg. C...............	..	40	40	40
Temperature of copper above incoming cooling medium in deg. C.	10	50	90	130

Based on the assumption that the total heat loss is constant for the four cases under consideration, it follows that the temperature rise of the cooling medium is also constant (a 10 deg. C. rise being assumed). If, then, the volume of the cooling medium be doubled, its outgoing temperature will be reduced by one-half (that is, 5 degrees) and the temperature of the surface of the insulated coil as well as the temperature of the copper will also be reduced by only this amount and not in proportion to the increase in the flow of the cooling medium except in the first case in which the coil has no insulation. From this it follows

that the greater the thickness of the insulation, the smaller will be the effect of increasing the cooling medium in the lowering of the temperature of the copper.

As it is essential to design for a uniform temperature for all conditions, it is necessary to reduce the loss per unit of area at the surface of the insulation in proportion to the increase in the insulation thickness. In small coils such as used for regulator windings, the external area is increased appreciably by increasing the thickness of the insulation. The area is not, however, increased in the same ratio as the thickness, and so a decrease in the heat to be dissipated per unit of area must always be obtained by decreasing the actual loss in the conductor itself, that is, by increasing the copper section or using a lower current density.

In general, the thicker the insulation on the outside of a coil, the more insulation is required between the conductors composing the coil. As the amount of insulation increases, there is a greater retardation of the flow of heat to the surface of the coil and a greater difference between the temperature of the copper and that of the cooling medium. The internal temperature must, however, obviously be kept within a limit not detrimental to the insulating materials, and the insulation therefore limits the voltages for which regulators or any slot-wound machines can be designed.

Dissipation of Heat

Under operating conditions, the maximum temperature exists at the center of that part of the coil which is embedded in the iron core. The heat loss of this section is conducted through the insulation to the core, and along the conductors to the end portion where it can more readily be dissipated. There is, however, a loss (that is, a drop

in temperature) in such a transmission, not only within the coil, but also at its contact with the cooling medium. If the regulator is of the oil-immersed type, there is a still further drop between the oil and the tank or radiator,

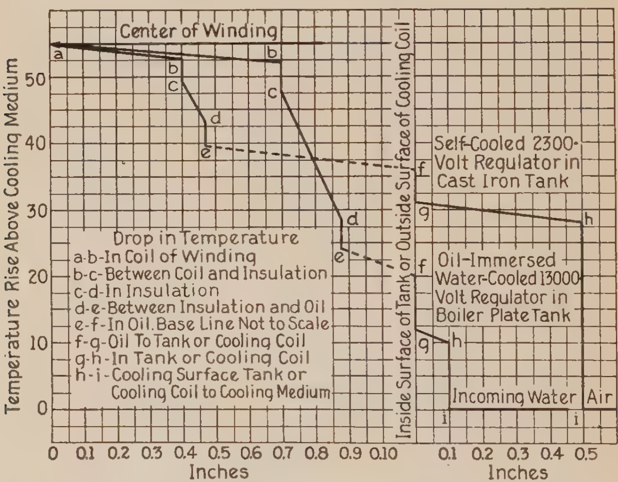


Fig. 73
Temperature Gradient Between Center of Coil Winding and Cooling Medium

and also between the tank or radiator and the final cooling medium. This is illustrated by the curves in Fig. 73 which show the temperature gradients from the center of the coil winding to the cooling medium of an average-sized oil-immersed self-cooled low-voltage regulator assembled in a cast iron tank and also of a large oil-immersed water-cooled high-voltage regulator assembled in a boiler plate tank.

The values given show the approximate relations of temperatures in a plane passing through the center line of the windings and cores or, in other words, approximately

halfway up in the tank. All temperatures are lower at the bottom than at the top. The copper temperatures given approximate those obtained by resistance measurements. The maximum hot spot temperature of the coil does not exceed the value given by more than 10 deg. C.

Referring to the curves, the temperature gradient in the copper of which the coil is wound is small, but it is increased by the insulating material between the turns of the coil. There is a very appreciable temperature drop between the surface of the bare coil and the insulation around the coil due to the imperfect contact between the two. The temperature drop through the insulation is high because of the poor heat conductivity of this material and depends on the insulating material used and on its thickness, as already explained.

There is again an abrupt temperature change between the surface of the insulation and the oil. This is due to a thin film of oil in immediate contact with the insulation. This film remains in contact with the insulation because of the adhesive force between any liquid and a solid. The adhesive force is sufficient to hold this film stationary, and since oil is a poor conductor of heat, the temperature drop is high compared with the temperature drop in the main body of the oil. The main body of the oil is, however, circulating and is successively heated by the copper and cooled by the radiating surface of the cooling medium. A similar temperature drop occurs between the oil and the surface of the cooling medium. This temperature change is higher in the water-cooled design than in the self-cooled because, per unit of heat transmitted, the surface of the cooling coil is smaller than the tank surface of the self-cooled regulator. A small temperature drop occurs, in the walls of the tank and cooling coil, depending on their

thickness. The final temperature drop is between the outside surface of the tank of the self-cooled regulator and the air, and between the inside surface of the cooling coil and the water in the coil.

The temperature drop between the oil container or tank of a self-cooled regulator and the air is exceedingly high. It is approximately one-half of the total temperature difference between the copper and the air. This great difference in temperature results from the low specific heat of the air and, therefore, from the relatively large volume of air which must come into direct contact with the tank in order to carry off the heat loss. Due to the relatively small difference between the specific weights of the heated air adjacent to the tank and the cooler surrounding air, the pressure causing the upward flow of air adjacent to the tank is small. The volume of air available for cooling is therefore limited and depends, not only on the difference between the temperatures of the tank and the air, but also on the nature of the surface exposed to the air. In the water-cooled design, the temperature drop due to the contact between the cooling coil and the water is comparatively small; first, because of the relatively small adhesion of the water to the walls of the coil; second, because water is a much better conductor of heat than oil; and, third, because of the comparatively high rate of flow of the water through the cooling coil. With a small diameter of cooling coil and a comparatively high rate of flow of the water, the flowing water comes into more intimate contact with the walls of the coil. It is therefore safe to assume that, at any section in the cooling coil, the water is of a uniform temperature. The temperature difference shown in the curve is that between ingoing and outgoing water.

Increase in Amount of Cooling Medium

A study of the temperature gradients given in Fig. 73 clearly indicates that the output of a self-cooled low-voltage regulator can be very appreciably increased by forced cooling, but that the output of an artificially cooled high-voltage regulator can not be much increased by increasing the amount of the cooling medium because of the great difference between the temperature of the copper and the oil due to the insulation around the winding. Stated more directly, the increase in the output is a function of the design and does not depend entirely on the amount of cooling medium supplied.

Self-Cooled Regulators

The majority of regulators used are of relatively small kv-a. capacity, and can be built more economically in the oil-immersed self-cooled design than for any other method of cooling. Such regulators are assembled in cast iron ribbed tanks, in corrugated sheet iron tanks, or in boiler plate tanks arranged with a single or multiple row of external tubes for increasing the radiating surface exposed to the air.

The maximum dissipation of heat to the air, per unit area of surface exposed, is obtained from a flat dull-black surface, and under normal operating conditions of electrical apparatus, the radiation loss is about one-third and the convection loss about two-thirds of the total loss dissipated. The use of ribs, corrugations and projections increases the convection loss but it does not increase the radiation loss. In the cast iron ribbed tank, the convection loss depends upon the cross section of the ribs and also upon their spacing. The former determines the conduction of the heat to the surface of the ribs and the latter determines the

amount of air which will flow between the ribs for a given difference in the temperature of the ribs at the floor and at the top of the tank. By properly proportioning the ribs and their spacing, a very appreciable increase is obtained in the amount of heat dissipated. This increase is, however, entirely due to the convection air currents.

In the corrugated sheet iron tank, the convection loss depends upon the design of the corrugations as well as upon the area of the developed surface. The corrugations should preferably be of such width and depth as to allow a flow of air on the outside and a flow of oil on the inside inversely proportional to their specific heat values. This requirement demands a much wider opening between the corrugations exposed to the air than between those exposed to the oil, for, as previously stated, the heat capacity of oil is twenty-five times as great as that of air per unit of volume.

In the proportioning of the corrugations, allowances must, however, be made for the difference in the fluidity of the oil and air as well as for the difference in their adhesive qualities. Moreover, because of the small pressures causing the circulation of both the oil and the air, and in order to facilitate the flow of each as much as possible, the corrugations should be well rounded and should have no angles or projections. Based on the heat radiated per unit area of developed surface, shallow corrugations are more efficient and less costly than deep corrugations. The depth of the corrugations must, however, be determined from the amount of heat to be dissipated rather than by their efficiency in dissipation.

For regulators which require a rigid cast iron spider to support the stationary sheet iron core, a cast iron tank, in which the punchings can be assembled directly, is less

expensive than a sheet iron tank which also would require a separate cast iron spider.

The smaller sizes of regulators are therefore assembled in cast iron ribbed tanks which also constitute the stator frames or spiders. These tanks are cast with ribs on the outside, and in the larger sizes, on the inside as well so as to obtain greater surfaces between the tank and the air and between the tank and the oil. The cast iron tank used as a stator frame has an added efficiency in that a considerable percentage of the core is in direct contact with the tank and thereby eliminates the temperature drop (through the oil) of that portion of the heat loss conducted directly from the core to the tank.

As has already been stated, the dissipation of the heat from the laminations is almost entirely through the edges, that is, parallel with the laminations. For this reason, the internal ribs for supporting the punchings are exceptionally wide. The openings at the corners of the tank are, however, sufficient for a free circulation of the oil. The efficiency of this arrangement is indicated by the higher temperature of that portion of the tank opposite the ribs which support the core. Because the cast iron tank requires less floor space than the corrugated tank and because the former contains a smaller amount of oil with consequent decreased fire risk, the use of tanks of this design is highly desirable for feeder regulators in all cases where it is possible to obtain a sufficient radiating surface for a reasonable cost.

Owing to difficulties in casting large tanks and in obtaining a sufficient radiating surface, larger sizes of regulators are assembled in a separate spider and the complete regulator is then assembled in a corrugated sheet iron tank. The corrugations used have a much

greater developed surface than it is practical to obtain with a cast iron tank, and in shape and size they are so designed as to obtain the maximum dissipation of heat.

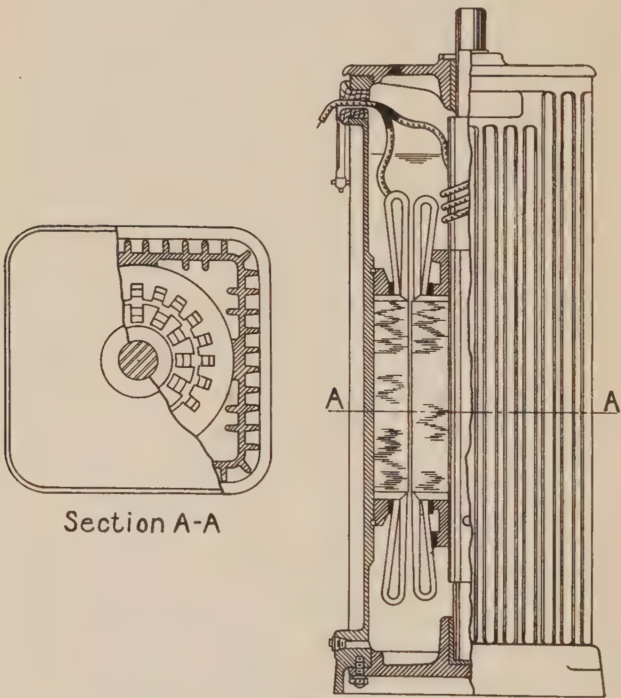


Fig. 74
Construction Detail of Three-Phase Induction Voltage Regulator in Ribbed Cast Iron Tank

Boiler plate tanks with single or multiple rows of tubes or radiators are used for the largest sizes of self-cooled machines; but as previously indicated, artificially cooled regulators, except in the smaller sizes, are less expensive and occupy a much smaller floor space than the self-cooled design.

All regulators built by the General Electric Company are designed so as to satisfy all of the preceding requirements, and the oil-immersed type has been adopted as the

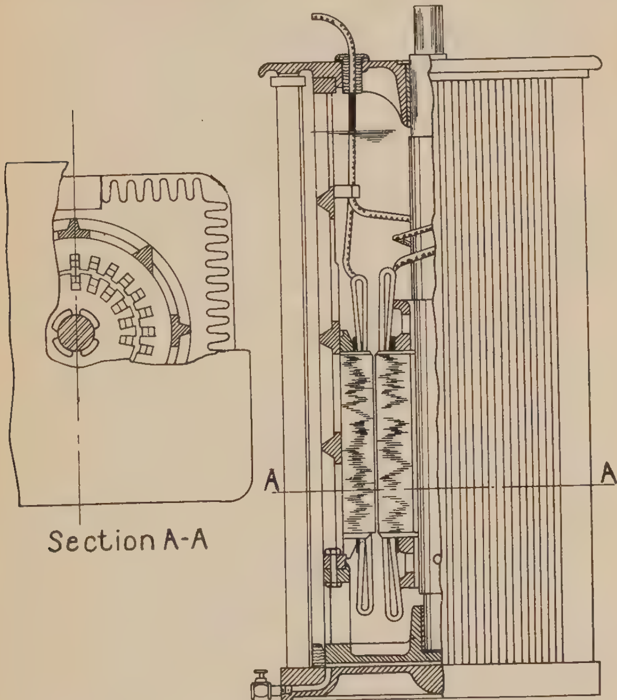


Fig. 75
Construction Detail of Three-Phase Induction Voltage Regulator in Corrugated Sheet Iron Tank

standard arrangement. The section of the windings and the copper densities are varied to suit the insulation and temperature requirements. The coils are spaced so as to permit a free oil circulation and also so as to present as large a surface to the oil as possible. The tanks and the cooling coils have ample radiating surfaces and are so

arranged that, under normal conditions, the maximum temperature of the copper is well within the safe limit with regard to the heating of the coil insulation.

Fig. 74 shows the arrangement used for all standard sizes of regulators from 5 to 70 kv-a. for both single-phase

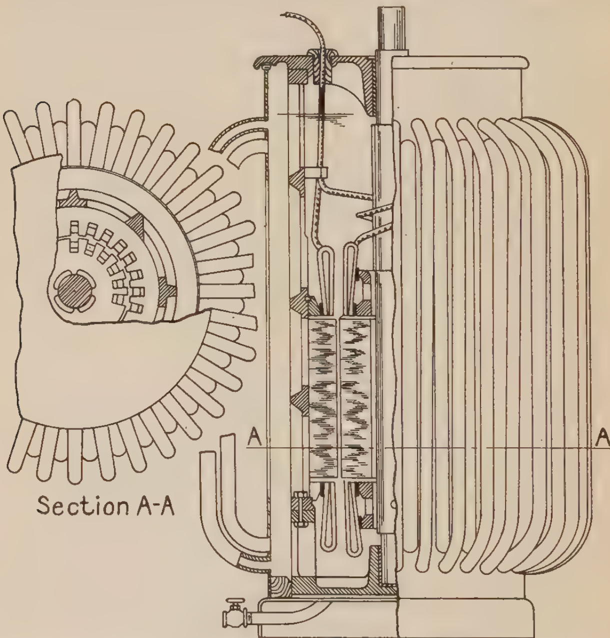


Fig. 76
Construction Detail of Three-Phase Induction Voltage Regulator in Tubular Boiler Plate Tank

and polyphase designs wound for 2300 volts 60 cycles, and for corresponding sizes for other voltages and frequencies. The heated oil passes up along the outside of the secondary core and up the gap between the primary and secondary cores and down the sides of the cast iron tank. The heat is dissipated by the tank and the external ribs. All sizes

assembled in cast iron tanks are of the oil-immersed self-cooled type, for the reason that the saving obtainable by using smaller parts for any given kv-a. capacity of regulator so assembled is less than the cost of providing means for artificial cooling.

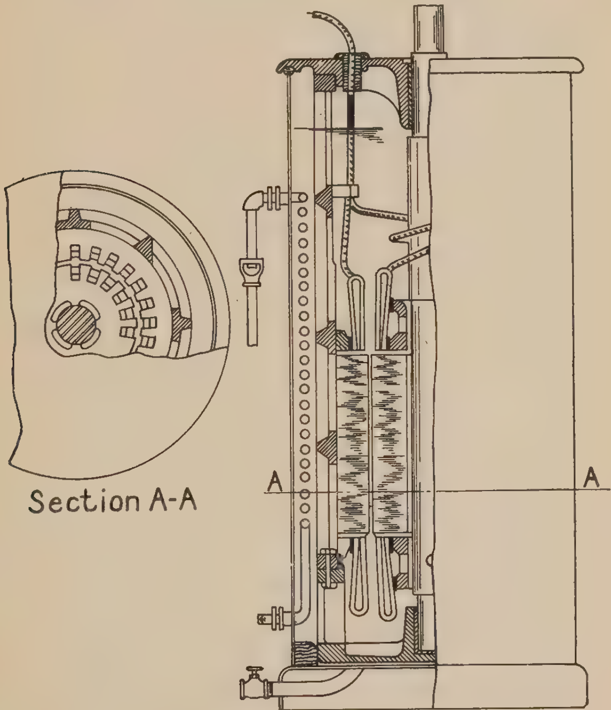


Fig. 77
Construction Detail of Three-Phase Induction Voltage Regulator in Boiler Plate Tank

The arrangement shown in Fig. 75 is used for self-cooled regulators from 70 to about 300 kv-a.; that shown in Fig. 76 is used for still larger sizes. In these designs, the oil passes up along the outside of the secondary core and

up the gap and also up the ventilating ducts along the shaft and then down the side of the tank and through the cooling tubes.

Artificially Cooled Regulators

The arrangement of the oil-immersed water-cooled design is shown in Fig. 77. The oil circulation is the same as shown in Fig. 76 except that the cooling is effected by the circular coil of pipe placed in the tank and through which water is circulated at a predetermined rate so as to allow for about 10 deg. C. rise in the temperature of the water. The water should always be fed into the bottom of the coil so as to insure that the pipe will be full at all times. The regulating valve should be placed at the intake in order to relieve the pressure on the coil. The outlet should be arranged as shown in Figs. 51 and 77. The discharge cup is furnished with the regulator and serves as an indicator of the water flow.

A regulator of the forced-oil design is similar to one of the oil- and water-cooled types but its tank contains no cooling coil. A cooling coil external to the regulator is, however, necessary and the oil itself is circulated in the cooling coil. This cooling coil may be immersed in flowing water or it may be arranged on a frame and exposed to the air. The hot oil from the top of the regulator tank is forced through the cooling coil by a pump and is returned to the bottom of the regulator tank after being cooled. Deflectors are arranged to obtain a proper distribution of the oil through the coils and core so as to insure a uniform temperature. The oil forced into the bottom of the regulator tank is discharged through a drain at the top. Gravity is depended upon to take care of this overflow and a valve at the intake is adjusted to regulate the flow.

Oil- and water-cooled regulators and forced-oil regulators should be provided with an alarm thermometer to indicate a rising or dangerous temperature of the oil due to overload or to a stoppage in the water or oil circulation.

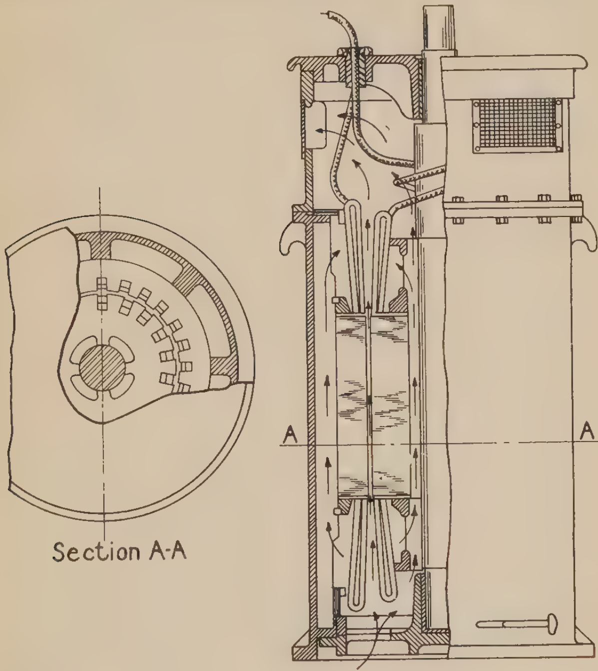


Fig. 78
Construction Detail of Three-Phase Induction Voltage Regulator in Boiler Plate Tank (Air-Blast Design)

Fig. 78 shows the forced air-cooled type of regulator. This design is arranged with deflectors, similar to the forced-oil type, to insure a proper distribution of air. The air should be screened or filtered to exclude dust and dirt which would otherwise accumulate on and between the coils, which accumulation would not only restrict

the air passages, but would also afford an opportunity for the deposit of moisture, and thereby endanger the safety of the apparatus.

The cast iron tank design shown in Figs. 45 and 74 can be arranged for forced-air cooling by providing holes in the bottom and in the top of the tank. This arrangement has been used in a number of instances where the fire insurance regulations have prohibited oil. This same design also has been used for the forced-oil type to increase the output, but it is not economical to install a circulating pump and cooling system especially for this purpose. To increase the output to some extent in an emergency, fans have been used to increase the circulation of the air and the tanks have even been placed in larger tanks somewhat lower than the outlets in the regulator and water circulated in the auxiliary tank. All of these methods are, however, only expedients for temporarily increasing the output of the regulator. As already indicated, the output of the artificially cooled regulators can also be somewhat increased by increasing the amount of the cooling medium.

Cooling Medium

The volume of the cooling medium supplied to a regulator through any given pipe or duct varies as the square root of the pressure; that is, to double the volume, four times the pressure is required. The pressure required to force the normal amount of water through the cooling coil of a regulator is approximately 5 lb. per sq. in. The volume of water must be regulated by a valve at the intake of the cooling coil.

The air-blast design of regulator requires from three-eighths to three-quarters of an ounce pressure per square

inch. The volume of air is regulated by a damper in the base of the regulator.

The overload which can be carried by the regulator as a result of increasing the cooling medium depends, however, as already indicated, on the amount of insulation within and on the outside of the coils, that is, it depends on the voltage of the circuit for which the regulator is wound and insulated. Regulators wound for the lower voltages can safely carry a much larger overload continuously than those wound for the higher voltages. In other words, the overload which a regulator will carry continuously by increasing the cooling medium depends upon the details of the design to a much greater extent than on the increase in the quantity of the cooling medium.

The volume of the cooling medium required for any design and kv-a. capacity of regulator necessarily depends upon the heat loss to be dissipated and upon the specific heat capacity of the cooling medium used. For artificially cooled regulators, it is recommended that the quantity of cooling medium supplied be sufficient to limit the temperature rise in the medium to 10 deg. C., in which case the following table applies:

2630 watts loss requires 1 gal. of water per minute.
1180 watts loss requires 1 gal. of oil per minute.
580 watts loss requires 100 cu. ft. of air per minute.

If the total loss in the regulator be known, the necessary amount of the cooling medium can readily be ascertained from the table, and as a safety precaution, the amount determined should be maintained regardless of the load on the regulator.

SECTION XI
TESTING OF REGULATORS

All induction regulators (both single-phase and polyphase) manufactured by the General Electric Company are given the following standard tests which are made in the order listed:

1. Cold resistance
2. Ratio
3. Polarity
4. Core loss and exciting current
5. Impedance
6. Noise test
7. High potential
8. Induced voltage
9. Test of auxiliaries
10. Checking diagram of connections
11. Inspection for oil leakage

Cold Resistance

A thermometer is suspended inside of the regulator and the regulator is allowed to stand in the testing department until it is safe to assume that the temperature of the windings is the same as that of the oil or air in the regulator as registered by the thermometer. Resistances of all phases and parallel circuits brought outside of the regulator of both the primary and the secondary windings are then taken by the drop-in-potential method. The direct current used is always somewhat less than the full-load current of the regulator. The results of the readings are then corrected to give the resistance at 75 deg. C.

Ratio

The shunt winding of the regulator is connected across a circuit of the proper voltage and frequency and the secondary winding is connected in series with this

circuit; that is, the regulator is connected as for normal operation. Voltage readings are taken directly across the series winding and across the circuit including the series winding. These readings are made with the regulator in the maximum boosting, maximum lowering, and neutral positions. The voltage directly across the series winding of a single-phase regulator is the same in both the maximum boost and maximum lower positions and is zero at neutral; the voltages across the secondaries of a polyphase machine are equal and constant throughout the range of control, as already explained.

The resultant voltage of the supply circuit and the secondary voltage of the regulator (that is, the regulated voltage) for both single-phase and polyphase designs will, however, be as shown in Fig. 6. If the windings of a polyphase regulator are connected incorrectly, the resultant voltages across the phases may be unbalanced or the maximum boost, maximum lower, and neutral positions may not be at the corresponding positions of the segment. This discrepancy can be corrected by the proper combination of series and shunt windings.

After test, both the primary and the secondary leads of the regulator are tagged to show the proper connection between the windings.

Polarity

The polarity of the winding is always checked during the ratio test to insure that a right-handed or clockwise rotation of the handwheel or operating handle lowers the voltage of the line in which the regulator is connected.

Core Loss and Magnetizing Current

The core loss and magnetizing current test is always taken with the proper voltage and frequency supplied by a

generator having a sine wave and with the regulator in the maximum boosting position.

The magnetizing current of both single-phase and polyphase regulators, as well as the core loss readings in the polyphase type, is practically constant for all positions

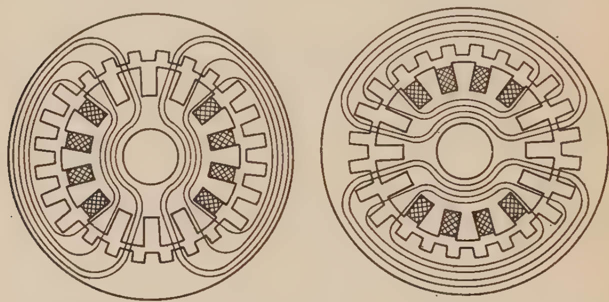


Fig. 79
Flux Distribution in Single-Phase Voltage Regulator Core

of the armature. The core loss in the single-phase type may vary, depending upon the design. In single-phase designs in which the vacant slots in the stationary core are shallower than the winding slots, or in designs in which they are omitted altogether, the core loss is usually less at the neutral position than at any other position. This is due to the increased cross section of the secondary core immediately behind the vacant slots and the correspondingly decreased magnetic density in this section of the secondary core when the armature is in the neutral position. This is illustrated in Fig. 79 which shows the core in the two positons, and in Fig. 80 which shows the variation in core loss. The average of the core loss throughout the range of regulation should, logically, be used as the basis for calculating efficiency for the reason that the regulator is as

likely to be in any one position as in any other, but for convenience, the loss in the maximum position is generally used as the basis for all guarantees.

The core loss in a polyphase regulator is considerably higher than in the single-phase design. In the single-phase

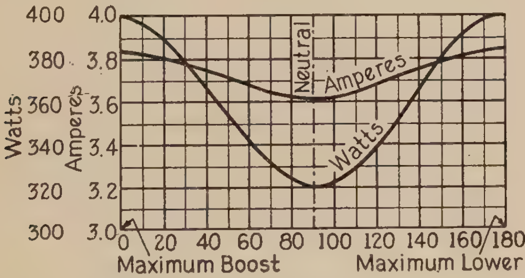


Fig. 80
Core Loss and Magnetizing Current of a Standard Single-Phase Regulator for Various Positions of Armature

regulator, the iron loss is due to the magnetization and demagnetization of the core as in a transformer, but in the polyphase design, it is due not only to this cycle of magnetization but also to the rotation of the flux, as already explained. This rotation of the flux increases both the hysteresis loss and the eddy current loss.

Core Loss Separation Test

The loss reading given by the wattmeters consists of the copper loss due to magnetizing current and the loss in the sheet iron. The latter loss consists of hysteresis and eddy current losses. These losses may be segregated by a separation test. The test consists in taking loss readings at various frequencies, but with the core at the same flux density for all readings, and basing all readings on the flux density for normal frequency and voltage. The eddy current

losses depend on the thickness of the sheet iron laminations and upon their electrical conductivity. These losses are a function of the frequency. The hysteresis losses are due

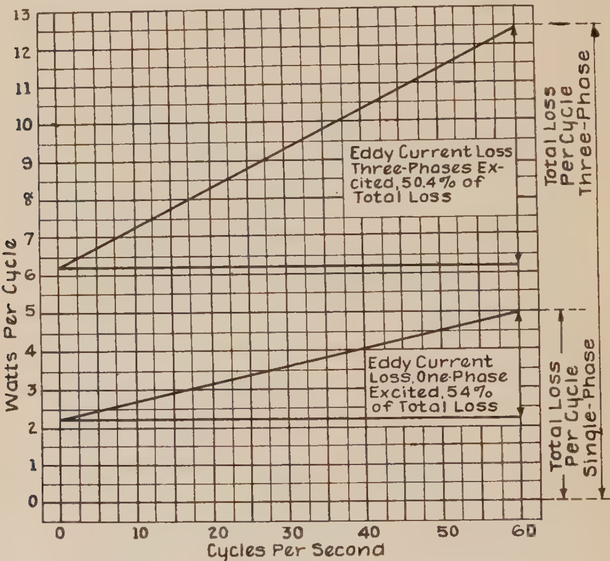


Fig. 81
Core Loss Separation Test on a 40 Kv-a., Three-Phase, 60-Cycle Regulator

to the magnetic lag in the iron. This loss is constant per cycle for a given density regardless of the frequency.

The copper loss due to excitation must be deducted from the net watt readings and the results can then be plotted as shown in Fig. 81. The data for both curves here shown were obtained on a three-phase regulator and in both cases the core was maintained at the same flux density. The upper curves give the losses in the core when excited three-phase, and the lower curves give the losses

when excited single-phase. Their comparison will serve to illustrate the difference in core loss due to single-phase and polyphase excitation. In standard designs, the difference in the core losses of the single-phase and the polyphase regulators is not so great as indicated, because the former is normally operated at a higher flux density than the latter. The increase in the magnetizing current due to very high flux density is, however, a limiting feature which prevents the operation of the single-phase core at the same loss as the core of the three-phase design.

The curves given show the importance of reducing the eddy current loss in the core. This loss is occasioned by local circulatory or eddy currents induced in the sheet iron laminations of which the core is built up or in the core itself. The intensity of these waste currents (and, hence, the amount of the loss) can be reduced by increasing the resistance of the path through which they flow. This can be accomplished: by using thin laminations; by insulating the laminations from each other; by punching the laminations with dies of the highest grade; and by using punchings of silicon steel.

The use of thin laminations increases the resistance of the path of the eddy currents across the core because of the numerous contact surfaces interposed. The resistance which these surfaces offer to the flow of current is further increased by the film of insulating material applied to each lamination. The use of only the highest grade of dies in punching the laminations eliminates the occurrence of burrs at the edges as these would serve to bridge over the laminations and so minimize the effect of the preceding two precautions. Resistance to the flow of these currents within each lamination is increased by the crystalline structure of the silicon steel from which they are punched.

It also is necessary to use special precautions in doing any machine work on the cores, for any machining operation is likely to burr over the edges of the laminations and thus

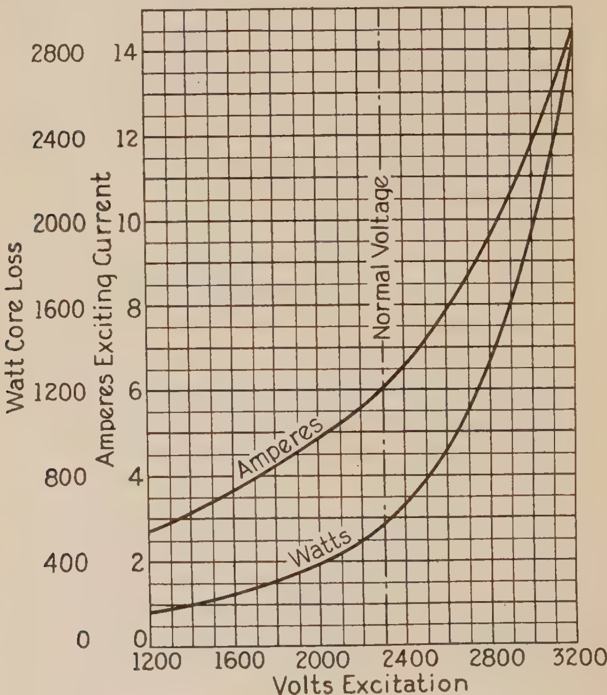


Fig. 82

No-Load Loss and Exciting Current by Varying Voltage on a Single-Phase, 60-Cycle, 2300-Volt Regulator

establish contact between adjacent laminations thereby aiding the flow of eddy currents. Any machining operation also increases the hysteresis loss because of the change in the structure of the iron itself which results from the machining operation.

Special Wattmeters

With the ordinary commercial instruments, it is practically impossible to obtain accurate core loss readings on a machine having an air gap, because of the low power-factor. The magnetizing current may be 25 per cent and the actual loss only 2 per cent. This gives a power-factor of 8 per cent. For all core loss readings, low power-factor wattmeters especially built for such purposes are, therefore, always used in the factory test. Fig. 82 gives the no-load loss and magnetizing current curves for one of the standard designs of single-phase regulators. These curves are characteristic of all regulator designs and serve to show the inadvisability of operating this type of apparatus at a voltage much higher than the normal rating because of the rapid increase in both core loss and magnetizing current.

Impedance

The impedance test consists in determining the voltage required to force full-load current through both shunt and series windings, and the loss in the copper due to full-load current. One winding is short-circuited through an ammeter, and sufficient voltage (at the proper frequency) is applied to the other winding to obtain full-load current through the windings short-circuited. The voltage required is then noted. The ratio of this voltage to the normal no-load voltage represents the impedance drop in per cent. Wattmeter readings also are taken and these readings less the core loss at the impedance voltage represents the actual loss in the copper due to the full-load current.

The impedance test can be taken by short-circuiting either the primary or the secondary of a polyphase regulator, but the primary must be the winding short-circuited in the single-phase type, in case this test is taken in any

other than the maximum position, because of the already short-circuited short-circuit winding on the armature.

Impedance Volts

The impedance voltage drop consists of two components at right angles to each other: namely, the resistance

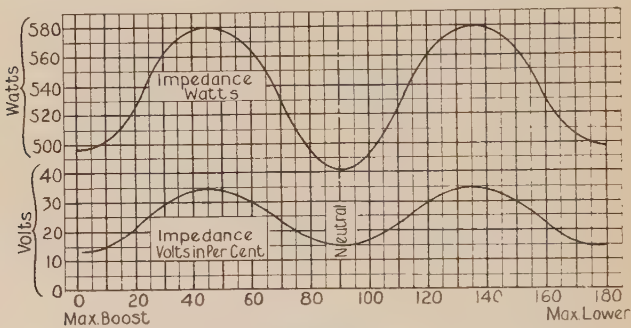


Fig. 83

Impedance Volts and Watts of a Standard 60-Cycle, Single-Phase Regulator

drop in phase with the line current, and the reactance drop at right angles to it. Their effect upon the induced voltage of the regulator is identical to similar voltage drops in a feeder. These have already been explained.

Both the impedance volts and watts are at their lowest value when the center of the primary coils is opposite the center of the secondary coils, that is, when the magnetic fluxes of the two coils are mutually interlinked. In a single-phase regulator, there are three such positions: at maximum boost; at neutral (that is, with the series winding opposite the short-circuited winding); and at maximum lower. An impedance curve of a single-phase regulator is shown in Fig. 83. The higher impedance between either of the maximum positions and the neutral position is due

to the flux distortion caused by the interlinking of the flux of the secondary coils with the fluxes of both the primary winding and the short-circuited winding. These two windings are at right angles to each other and are both displaced at an angle of 45 degrees from the secondary, as has been previously explained. This flux distortion also causes a greater tooth torque at these positions and, consequently, there is a greater tendency for the regulator to vibrate.

In the polyphase type of regulator, a similar condition prevails; the minimum voltage and wattage values occur when any primary is directly opposite any secondary regardless of its phase. In either the single-phase or polyphase regulators, the curve is not regular but is more or less jagged. The irregularity depends on the distribution of the magnetic flux in the air gap for the various relative positions of rotor and stator. In other words, the irregularity depends on the relative widths of the teeth and slots in both members of the core.

Impedance Watts

The net copper loss, as determined in this test, is the actual loss in watts which must be dissipated from the surface of the coils in the form of heat. As already stated, this loss may be considerably greater than that represented by the current squared times the resistance. Its magnitude depends on the size and shape of copper used for the windings, its arrangement in the slots, and on the frequency of the circuit in which the regulator is used. In the case of a polyphase regulator, this loss is practically uniform throughout the entire range of control, but in the single-phase design, it may vary depending on the wire used for the short-circuited winding. If the cross section per ampere

in the short-circuited winding is the same as that in the shunt winding, and if the size and section of copper and coils are also identical, the loss will be fairly constant in the

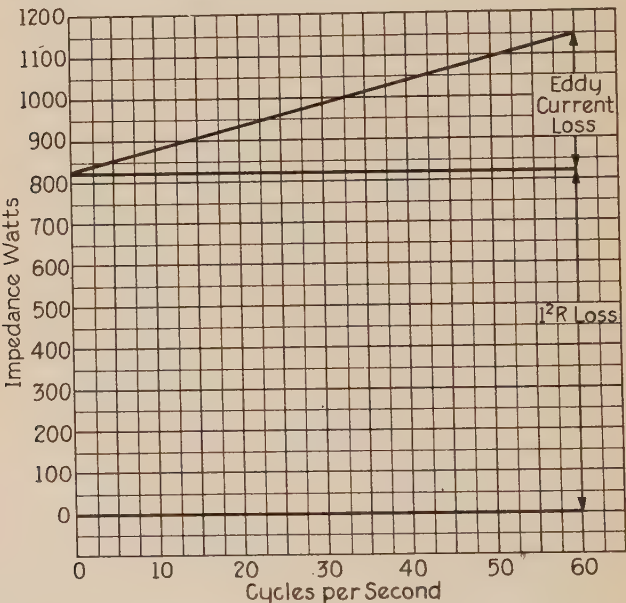


Fig. 84

Copper Loss Separation Test on a 72 Kv-a., Single-Phase Regulator by Wattmeter at 25 Deg. C. with Regulator in Neutral Position

maximum positions of the regulator and in the neutral position. If a decreased total cross section of copper is used for the short-circuited winding or if this winding is made of conductors having a large cross section, the loss in the neutral position of the regulator may greatly exceed the loss at the maximum boost or lower positions.

As will be noted by the curve given, the impedance watts between the maximum positions and the neutral are

a maximum, and for the same reason that the impedance voltage is higher in these positions. Regulators manufactured by the General Electric Company are always designed with a short-circuited winding consisting of stranded cable of practically the same section per ampere as that of the primary winding. This insures, as nearly as is possible, a uniform loss for all positions of the armature and, hence, a uniform rise in temperature.

Copper Loss Separation Test

As with the iron losses, the losses in the conductor may be investigated and separated into their components by taking impedance watts readings at different frequencies but maintaining the same current. Fig. 84 illustrates such a series of tests and serves to show that the eddy current loss in the windings increases with an increase in frequency. The I^2R loss is necessarily constant for all frequencies. A winding or copper section suitable for a low-frequency circuit may therefore be entirely unsuited for higher frequencies because of the increased heating due to the eddy currents in the copper.

Noise Test

Due to the limitations imposed by the design, by the variations in materials, and by the impracticability of absolutely correct machining, all regulators are inherently subject to vibration. Each regulator is therefore tested under full excitation and at no load, and with full-load current with the heat run connection. Both tests are taken while rotating the armature from the maximum boost to the maximum lower position.

In case the vibration is greater than allowable (that is, so that it is distinctly audible), the regulator is re-machined so as more nearly to equalize the air gap. The

rotor is placed in a lathe and the core is trued up with the bearing surfaces of the shaft. The stator is mounted on a vertical mill and is carefully lined up, usually from the step bearing. The cover fit is peened, a slight cut is taken from the core, and the cover fit is re-machined to size. After the cover is assembled in place, the top bearing is checked and relined and re-machined if necessary. This procedure, if accurately done, almost invariably eliminates the trouble.

Loose laminations may also cause noise and the core may require repressing and additional laminations.

High Potential

As a preliminary test during the assembling operation, a high-potential test of between two and three times normal operating voltage is applied between phases and to ground on both the primary and the secondary coils as soon as the windings are assembled in the slots and before they are permanently connected, and also after such connections have been made.

After the machine is completely assembled and the various preceding tests have been made, the high potential test between phases and to core is again applied so as to insure that all windings and connections are suitably insulated for the circuit to which the regulator will be connected. In testing between phases and to ground, all of the windings are connected to one or the other of the high potential test lines.

Induced Voltage

At least three times normal voltage is applied directly to the terminals of either the primary or secondary winding at a frequency sufficiently high to prevent the flow of a current higher than normal. In applying the voltage to one

winding, the other must be left open and the regulator must be in either maximum position. This potential test is applied for one minute and is followed by double potential applied for five minutes.

Referred to the applied and induced voltages, the factor of safety of the insulation to ground is usually about 10, and that between turns and layers may be as high as 500. Because of this, the high potential test and the induced voltage test in no way injure the insulation, but the voltages used are sufficiently high to detect serious weakness.

Test of Auxiliaries

The operating motors are always given the standard commercial tests usually applied to standard induction motors. These tests are made before the motor is mounted on the regulator, and in addition to them, a starting torque test is made by means of a Prony brake. After the motor is mounted on the regulator, it is again tested to determine the time which is required to operate the regulator from the maximum boost to the maximum lower position. With the brake properly adjusted, the starting current of the motor is noted and observations are made to determine the minimum voltage at which the motor will start. The minimum starting voltage allowable is not more than 80 per cent of the normal running voltage of the motor.

The freeness of the gearing is noted and the connections of the limit switch are checked. The trip pins on the regulator segment are then adjusted so that they will trip the limit switch at both the maximum and the minimum positions of the regulator. In the two-pole design of regulator, this adjustment is made in connection with the adjustment of the spring of the brake. The spring is adjusted so that, with the motor running at full speed,

the overtravel of the regulator segment will be equal to one-half of 1 per cent of the line voltage regulated.

The operating motor used with each design and size of regulator is also tested to determine the power required to operate the regulator under load and in the maximum torque position. All motors furnished are of ample capacity, so that with 80 per cent normal voltage applied to a motor, it will operate the regulator when carrying 50 per cent overload.

The magnetic brake furnished on the larger regulators is always wound for the same voltage and frequency as the operating motor and is tested for the minimum voltage at which it will operate. The minimum voltage for the operation of the brake must not exceed 80 per cent of its normal voltage. The current is measured with the brake open and closed. The resistance of the winding is measured, and double normal voltage at double frequency is applied for a period of five minutes. All auxiliaries are then given a high potential test to ground of 1000 volts. The operating voltage is always limited to 250 volts.

Checking Diagram of Connections

With every regulator there is furnished a diagram of the connections of the regulator and of all the auxiliaries to be used with it. The connections of the regulator itself and those of the auxiliaries mounted on the regulator cover are carefully checked. The same care is used in determining the correctness of the numbering of the leads. Hence, no errors in connecting should occur if this diagram is followed in installing the apparatus. The connections of such auxiliaries as are not mounted on the cover, but which may be furnished and used in conjunction with the regulator are not completely checked with the regulator connections

in individual cases, although the connections of the auxiliaries themselves are checked.

Inspection for Oil Leakage

Due to possible imperfections in castings, joints, and oil stops, each regulator is carefully inspected for oil leakage. This inspection is made after the regulator has been filled with hot oil for a period of six hours. This inspection is, however, not conclusive as oil leakage may not occur for days, weeks, or even months after the regulator is installed. The test does, however, serve to disclose any radical defects.

Special Tests

In addition to the standard tests enumerated, a series of special tests is made on each design of regulator, if this is feasible and if required for design data. Some of the special tests have already been indicated, but the principal tests of this character are as follows:

Heat Run

Heat runs under normal operating conditions are made on a number of regulators of each size and design. The heat run is continued until the various parts of the apparatus reach ultimate temperatures unless it can absolutely be predetermined from previous tests on practically duplicate machines that the losses and radiating surfaces are such as to preclude the possibility that the regulator will overheat or fail to meet the heating guarantees made upon it.

The regulator is connected as a transformer and is "loaded" on a water-box. It is then adjusted to the maximum boost position as in this position the loss is usually a maximum. Spirit thermometers are then placed in numerous positions inside of and outside on the regulator and in the cooling medium. Several resistance readings of each winding are then taken and the average value is used as a basis for determining the rise in temperature of that

winding. The temperature of the copper is also noted so that corrections can be made in the series of resistance readings taken during the test in case the temperature of the cooling medium should not remain constant. The load is then connected to the regulator and is carefully adjusted and maintained. During the test, resistance readings are taken hourly on all windings and with the same instruments that were used to measure cold resistance.

Hourly readings also are taken on all thermometers. The resistance measurements, cold and hot, give the rise in temperature of the copper; but, necessarily, only the average rise is thus determined. There may be hot spots particularly in that part of the winding which is embedded in the sheet iron core. The maximum temperature can, however, be determined experimentally by embedding thermocouples at various points in the windings themselves. Based on such investigations, regulators are so designed that no dangerous temperatures occur under normal conditions of operation and cooling.

If the regulator is artificially cooled, the amount of the cooling medium is measured. In addition to this, measurement is made of its incoming and outgoing temperature and the flow is adjusted for a predetermined rise in the temperature of the medium. This rise is usually 10 deg. C.

The results of the test are recorded and tabulated. The data obtained are then compared with the calculations and with similar test data obtained from other machines, and form a basis for future designs.

The volume of the cooling medium necessary is predetermined, and, as stated in the previous section, is based on the losses in the regulator and on the specified heat capacity of the cooling medium. The following figures are used, and the time in each case is based on one minute.

To raise 1 gal. of water 10 deg. C. requires 2630 watts.
To raise 1 gal. of oil 10 deg. C. requires 1180 watts.
To raise 1 cu. ft. of air 10 deg. C. requires 5.8 watts.

To find the necessary volume of the cooling medium required per minute for any given regulator, it is therefore necessary only to divide the total watts lost in the regulator when operating at normal load temperature by the watts per unit of the cooling medium required as obtained from the preceding table. In figuring the capacity of the blower for the air-blast type of regulator, a sufficient allowance should be made for leakage. An average figure for this allowance is 50 per cent.

To make the heat test properly, a 100 per cent power-factor load is required, but because of the large amount of power necessary, it is impractical to conduct this test on the larger regulators in the manner described, and it therefore becomes necessary to resort to other expedients. For heavy-current regulators, there is no simple method for testing one single-phase or one quarter-phase regulator; but a single three-phase machine is usually arranged as follows:

The primary is connected delta and is excited at normal frequency with the normal voltage per phase. The three phases of the secondary are connected in a similar delta but one connection is left open. The secondary windings, thus connected in series, are now connected to a separate generator and full-load single-phase current at approximately normal frequency is forced through them. This current, being single-phase, causes a corresponding single-phase circulating current to flow through the delta-connected primary winding and thus produces the copper loss, whereas the three-phase excitation produces the core loss.

If two single-phase or polyphase regulators of the same kv-a. capacity and for the same voltage and frequency are available, they may be tested by the motor-generator method.

To make the heat run test on single-phase regulators by this method, a polyphase source of supply is required, and for the following reason. If the primaries of two single-phase regulators are connected to a single-phase supply of the proper voltage and frequency, and if the secondaries are connected in parallel and bucking, and if the regulators are then adjusted so that full-load current flows in the series winding, this circulating current is wattless or nearly so. From previous considerations, it is obvious that the voltages in the secondary windings are in phase with but opposite to the impressed voltage, hence the secondary current must be at right angles thereto. This circulating current in the series windings causes a corresponding or ratio current to flow in the primary windings, which ratio current must also be at right angles to the applied voltage. As the magnetizing current is also at right angles to the applied voltage, the ratio current and magnetizing current add directly instead of at right angles as under normal operating conditions. Hence, as the regulators are bucking and the current in the series windings is a circulating one, the current in the primary of one regulator will be the sum of the primary circulating current and the magnetizing current, whereas the current in the primary of the other regulator will be the difference between these two currents.

By adjusting both regulators, it is possible to obtain normal full-load current in both the primary and the secondary windings of one of the regulators. However, with a regulator in any other than a maximum position, any current in the series winding causes a current to flow in both the shunt and short-circuited windings (see Fig. 7), that is, adjusting the regulators as indicated merely shifts part of the ratio current from the shunt winding, where it can be measured, to the short-circuited winding where it

can not be measured. The current in the short-circuited winding causes a loss proportional to the square of the current flowing, which loss increases the temperature of the primary core and, hence, also the temperature of the shunt windings. Under normal operating conditions and with full-load current in the series windings, the current in the shunt winding decreases as the regulator is turned out of either maximum position, under which condition the current in the short-circuited winding increases as shown in Fig. 7. It is, therefore, obvious that this connection can not be used for the heat run.

However, by exciting both primary windings of the regulators from one phase of a two-phase generator and by connecting the series windings in series with each other, but bucking and in series with a variable voltage at right angles to the excitation voltage, as for instance a third regulator excited from the other phase of the two-phase generator, then with this arrangement and connection, it is possible to load one regulator so as to duplicate normal operating conditions.

Similar results may be obtained by the proper combination of the phases of a three-phase source of supply.

The regulator under test must be in the maximum boosting condition. A normal full-load current in the series winding will induce a corresponding or ratio current in the shunt winding. The magnetizing current will now, however, be at right angles to this ratio current as under normal operating conditions, and the heat run will show the correct heating.

Two three-phase regulators may be given the heat run test by the motor-generator method by connecting the primary windings of both regulators to a three-phase generator of the proper voltage and frequency and by

connecting the respective secondary windings of the two regulators in parallel with each other but not to any source of power. With both regulators in the neutral

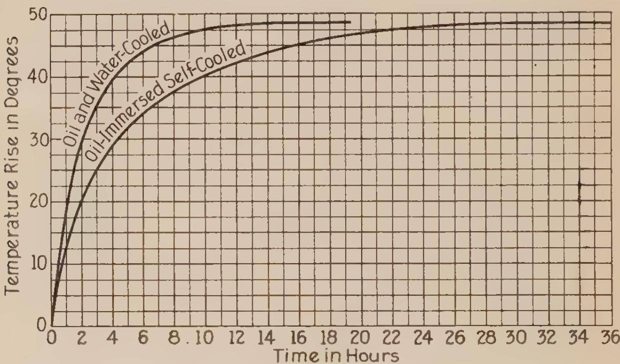


Fig. 85
Induction Regulator Heat Run Characteristics
(Temperature Rise of Winding)

position, no current will flow in the series windings; but by shifting one regulator from this position, current will be caused to flow. By adjusting this current so as to be equal to the full-load current, a corresponding or ratio current will be caused to circulate in the primary windings. This current is, however, at right angles to the magnetizing current as indicated in Section IV and, hence, the heating of the regulator in the neutral position will be the same as under normal full-load conditions.

Fig. 85 shows the increase in the temperature of the windings of a self-cooled oil-immersed regulator and a water-cooled oil-immersed machine when both machines are operating under normal conditions. The increase in the temperature of the artificially cooled regulator is very much faster because of the higher current densities in the wind-

ings, which produce greater heat losses per unit of weight or volume of copper. The windings in both designs ultimately however, reach the same temperature, or rather have the same temperature rise, if both regulators are operated under normal conditions of cooling.

Efficiency

The efficiency of a regulator should be based on the no-load induced voltage times full-load current. This kv-a. is, however, usually about 10 per cent greater than the rating stamped on the name plate, for the regulator rating is based, as previously stated, on a load of approximately 80 per cent power-factor. The over ratio in different designs of the same rating also varies because of the varied ratio of slots and the varied arrangements of the conductors in the slots. The efficiency must also be considered when the regulator is in the maximum boosting position for the reason that the output varies with the position of the armature (as, for instance, at the neutral position the output is zero), whereas the losses may remain constant for all positions.

Division of Iron and Copper Losses

The division of the iron and copper losses should also be particularly considered because the actual cost of supplying the losses depends on their relative relation to each other. The core loss is continuous for 24 hours a day while the copper loss varies as the square of the current regulated and is generally maintained at its maximum for only a few hours a day. Thus, from an operating standpoint, a high copper loss is generally preferable to a high core loss for the reason that the former is generally a maximum for a comparatively short period, whereas the latter is constant as long as the regulator is

connected, and is independent of the line current regulated. Hence regulators of identical rating may have the same full load efficiency, but the actual cost of supplying the

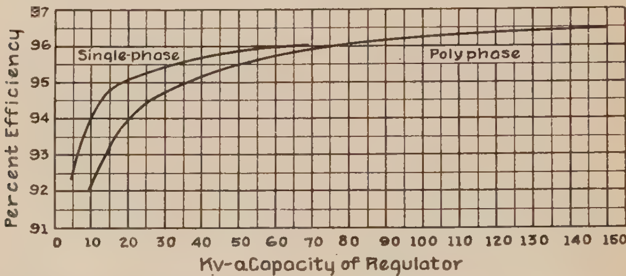


Fig. 86

Approximate Average Test Efficiencies of G-E Regulator Based on Impedance Watts and Core Loss at 100 Per Cent Load and Power-Factor and on the Name Plate Rating and at 75 Deg. C.

24-hour losses may be radically different. It would therefore seem preferable to base guarantees on segregated iron and copper losses, and guarantees on General Electric Company regulators are made on this basis.

The efficiency of the induction regulator is high compared with that of other apparatus of similar design. This is due primarily to the difficulties of cooling. The rotor or armature is stationary and the ventilation or cooling, even with an air blast, is much less efficient than usually obtained with a rotating armature. As shown in Fig. 86, the efficiencies of the standard designs of General Electric Company regulators vary from 91 per cent in the smaller sizes to over 96 per cent in the larger ones. The losses are so proportioned that the copper loss, as measured by a wattmeter, is approximately 60 per cent of the total loss.

Torque Test

A torque test is taken on one regulator of each design in order to check the actual power required to operate it with the amount calculated. The regulator torque to be overcome by the motor is that due to friction, to the tooth torque, and to the load.

The friction depends on the gearing, on the weight of the moving parts, and on the bearings.

The tooth torque depends on the number and on the relative widths of the slots and teeth in both the rotor and the stator. With the ideal proportions, the tooth torque is zero; but it will remain so only at no load, for the load current also produces a flux which more or less distorts and modifies the primary flux and, hence, produces a tooth torque. Moreover, it usually is not practical to design for the ideal conditions, and for this reason the tooth torque, especially in the single-phase regulator, is rather pronounced. This is illustrated in Fig. 40 which gives the torque measured directly on the shaft of a single-phase 34 kv-a. regulator carrying full load at 100 per cent power-factor.

For any given position of the armature, the load torque is proportional to the secondary current, but it is modified by the power-factor of the load as explained in Section VI.

The total torque required of the operating motor is determined as indicated in Figs. 65 and 66, by applying voltage to the operating motor. The tooth torque (and, in the smaller sizes of regulators, the rotating torque as illustrated in Figs. 40 to 43 inclusive) is, however, determined by disconnecting the gearing, attaching a lever arm directly to the regulator shaft, and measuring the torque by the means of a spring balance.

Guarantees

From the preceding sections, it might appear that the results of the tests of any design of regulator could be very accurately predetermined. Unfortunately, such is not the case.

In making a punching of a new design, or in making any modification of a standard design, the predetermining of the core loss is exceedingly difficult because the flux density in every integral part of the punching varies. In the core, the variation is as indicated by the flux lines in Fig. 79, and in the teeth, it is due to their varying section.

In a circular primary and secondary core such as shown in Fig. 79, but each having an infinite number of teeth, the flux density would vary from the positive to the negative pole as a sine curve. It would then be possible to determine the theoretical loss in both core and teeth of both the rotor and stator by integration. However, with the small number of teeth required by practical conditions, this theoretical flux distribution is greatly distorted and the only practical means of determining the loss with any degree of accuracy is by test.

In the single-phase regulator, the flux is alternating and the core loss is predetermined as in a transformer, but in the polyphase design, the flux is rotating. This flux rotation causes higher losses in the teeth and for these losses, as indicated by Fig. 81, additional allowances must be made. Even in a standard design of punching, the losses vary due to inequalities in the sheet iron itself because of differences in thickness and in composition. They also vary due to handling, punching, annealing, assembling, filing, and turning of the laminations and the core. For these reasons, the variation in the losses of duplicate regulators sometimes exceeds 20 per cent.

The losses in the copper are not subject to such wide variations, but differences exist in the section (due to inequalities in drawing or rolling) and in hardness, and both of these inequalities affect the resistance. The variation in the copper losses amounts to only from 2 to 3 per cent, but much greater differences may be caused by the eddy current losses which can not be predetermined with any degree of accuracy in high-current regulators or in regulators wound with a conductor of large section.

In making performance guarantees on this class of apparatus, it is therefore always necessary to provide a very ample margin, and while occasionally the actual losses exceed the estimated losses, they are in general considerably less. Consequently, when the actual losses are lower than guaranteed, the heating is also usually less than given in the specifications and less than required by the A.I.E.E. ruling. This is especially true for new designs for which there are no reliable test data on which to base guarantees, and on which even greater allowances than normal are therefore made.

The object of all tests is primarily to accumulate design data for use in future designs and to check the calculations and materials used.

Regardless, however, of the amount of test data available, some allowances always have to be made because of inequalities in materials, in the handling of materials, and in manufacturing. It therefore seems more reasonable to give performance guarantees based on the average test results obtained on any given size and design of regulator than to give guarantees which must positively be met by each individual unit. The basis on which guarantees are required or given should be designated in the specification.

SECTION XII

LIMITATIONS OF DESIGN

Regulators can be built for any voltage and for any current for which it is practicable to build generators or motors of corresponding sizes. However, regulators are used in series with distributing or transmission systems, and their kv-a. capacity is only about 10 per cent of the kv-a. capacity of the line to be regulated. Hence, this condition or application requires that regulators be wound for voltages and currents corresponding to those of generators or motors of very much larger kv-a. capacities. Comparatively small regulators are therefore required to be wound and insulated for relatively high voltages or high currents.

There is no difficulty in designing or building a 5 kv-a. regulator for 2300 volts and a 100 kv-a. regulator for voltages up to 13,000 volts, for either single-phase or polyphase circuits. Large regulators have also been built for currents of 10,000 amperes.

The limitations in the building of small regulators for high voltages are the mechanical difficulties of winding the shunt coils with wire sufficiently small to conform with the electrical requirements and the difficulties of providing proper insulation. The limitations imposed by high-current requirements are the making of suitable connections and the bringing of the series leads out of the tank or spider.

Exciting and Series Transformers

If small sizes of regulators are required for either high-voltage or high-current circuits, or if any size of regulator is desired for higher voltages or currents than can be handled in a regulator of reasonable design, it is necessary

to reduce the voltage or the current in the regulator by the use of auxiliary transformers for the shunt or the series winding, or for both of them.

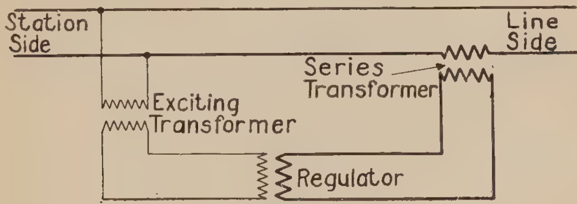


Fig. 87
Regulation of a Single-Phase High-Voltage Circuit

To control a circuit of high current, but of small kv-a. capacity (as required for small furnaces, calibration of instruments, or laboratory work), it is generally satisfactory to use a transformer in the secondary of the regulator only. To control a circuit of high-voltage but of small kv-a. capacity, both exciting and series transformers are required because of the difficulties of winding and insulating the regulator coils.

A diagram showing the connections of a single-phase regulator with both exciting and series transformers is shown in Fig. 87, and a diagram of a three-phase regulator similarly arranged is shown in Fig. 88. By using transformers of the proper ratios, a standard regulator of the kv-a. capacity required, or, in fact, one of any design whatever, may be used to regulate a circuit of any voltage or of any current capacity. The transformers must be somewhat larger than the rated kv-a. capacity of the regulator in order to carry the exciting current and the over ratio of the regulator in addition to its normal load, and they must be insulated for the potential of the line to which they are connected. In the three-phase

connection, it also is required that the transformers introduce no phase displacement, and they should preferably be Y-connected as shown. If a combination of Y and delta connections is used, a proper combination and

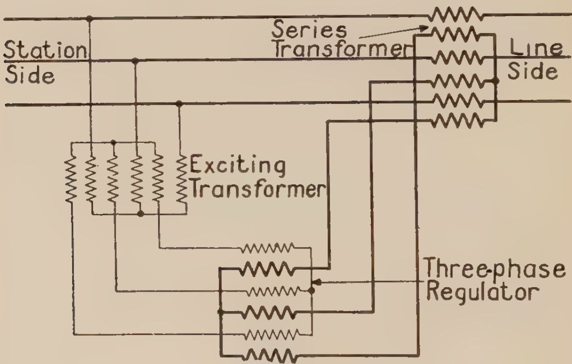


Fig. 88
Regulation of a Three-Phase High-Voltage Circuit

connection is required so that the regulator will boost or lower the line voltage as if it were connected directly in the line in the usual manner.

Aside from the above limitations and those imposed by heating and ventilation, there is no limit to the kv-a. capacity for which regulators can be designed. Regulators of from 100 watts to 1000 kv-a. and over have been built in both the single-phase and in the polyphase designs.

SECTION XIII

STANDARD SIZES OF REGULATORS

A number of standard designs of parts (including tanks, punchings, and mechanisms), have been developed for both single-phase and polyphase regulators of the oil-immersed type, and a full pattern and tool equipment is available for the building of regulators of from 5 to 1000 kv-a.

The majority of the regulators required are for 60-cycle 2300-volt circuits and vary from 5 to 70 kv-a. single-phase and from 10 to 100 kv-a. three-phase. These sizes have therefore been listed as standard and are usually carried in stock, so that better shipments as well as lower prices, can generally be obtained in these sizes. It is therefore advantageous to install a standard size of regulator if possible even if it is somewhat larger than the requirements demand.

Fig. 89 gives a tabulation of the standard sizes of single-phase regulators and their overall dimensions, weights, and time of operation. Fig. 90 gives similar data for the three-phase design assembled in the cast iron tank. Figs. 91 and 92 give approximate dimensions of the larger polyphase regulators of the self-cooled type for various sizes and wound for a number of standard line voltages and frequencies. Fig. 93 gives corresponding data for the artificially cooled type.

The tabulations accompanying Figs. 91, 92 and 93 give only the largest kv-a. capacity of regulator assembled in any given size of parts; any intermediate size of regulator is assembled in a tank of the next larger size, but of reduced height. The tables do not give all of the sizes of parts developed, nor do they include the air-blast design.

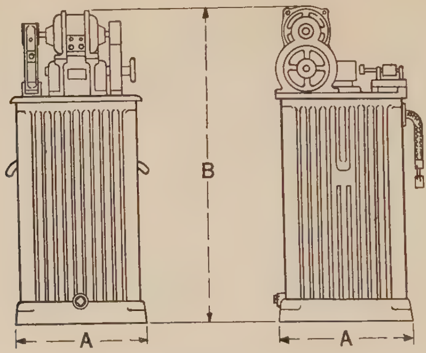


Fig. 89
Dimensions of G-E Standard Single-Phase, 2300-Volt, 60-Cycle, Self-Cooled Regulators in Cast Iron Tanks

REGULATOR CAPACITY in Amp.	INCREASE OR DECREASE IN LINE VOLTAGE		KV-A. CAPACITY OF REGULATOR	DIMENSIONS IN INCHES		NET WT. in Lb. (Apprx.)	NO. OF GAL. OF OIL	TIME OF OPERATION in Seconds
	Per Cent	Volts		A	B			
25	10.0	230	5.75	17⅝	49	950	13	8
50	7.5	173	8.6	17⅝	53	1100	15	8
50	10.0	230	11.5	17⅝	55	1200	16	8
75	7.5	173	13.0	17⅝	59	1300	18	8
75	10.0	230	17.25	17⅝	61½	1400	19	8
100	7.5	173	17.25	17⅝	61½	1400	19	8
100	10.0	230	23.0	21	63	1900	26	11
150	7.5	173	26.0	21	63	2000	26	11
150	10.0	230	34.5	21	70	2350	31	11
200	7.5	173	34.5	21	70	2350	31	11
200	10.0	230	46.0	21	80	2850	41	11
250	7.5	173	43.12	21	80	2850	41	11
250	10.0	230	57.5	25¼	81¼	3700	52	11
300	7.5	173	52.0	25¼	81¼	3700	52	11
300	10.0	230	69.0	25¼	84	4200	90	11

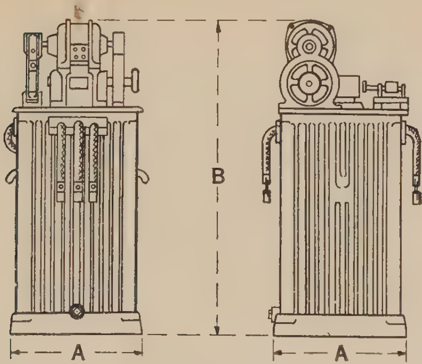


Fig. 90
Dimensions of G-E Standard Three-Phase, 2300-Volt, 60-Cycle, Self-Cooled Regulators in Cast Iron Tanks

REGULATOR CAPACITY in Amp.	INCREASE OR DECREASE IN LINE VOLTAGE		KV-A. CAPACITY REGULATOR	DIMENSIONS IN INCHES		NET WT. in Lb. (Apprx.)	NO. OF GAL. OF OIL	TIME OF OPERATION in Seconds
	Per Cent	Volts		A	B			
25	10	230	10	17⅝	59	1250	16	8
50	10	230	20	21	63	2050	26	11
75	10	230	30	21	70	2200	30	11
100	10	230	40	25¼	81¼	3450	60	11
150	10	230	60	25¼	87¼	3600	65	11

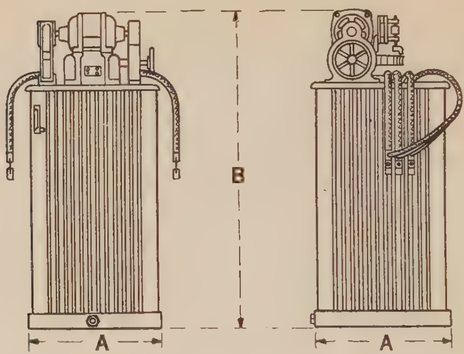


Fig. 91

Dimensions of G-E Three-Phase, 2300-, 4600-, 6600-, 13,200-Volt, 60- and 25-Cycle, Self-Cooled Regulators in Corrugated Sheet Iron Tanks

2300 Volts		4600 Volts		6600 Volts		13,200 Volts		DIMEN. IN IN.		NET WT. in Lb. (Aprx.)	NO. OF GAL. of OIL	TIME OF OPERATION in Seconds
AMP. of Feeder	KV-A. of Regulator	AMP. of Feeder	KV-A. of Regulator	AMP. of Feeder	KV-A. of Regulator	AMP. of Feeder	KV-A. of Regulator	A	B			
					60 CYCLES							
200	80	75	60	35.0	40	...	...	31½	86¾	4200	120	14
250	100	100	80	61.0	70	...	...	35	86⅞	6200	180	17
375	150	160	128	88.0	100	35	80	43	98⅛	8500	300	23
750	300	250	200	150.0	170	44	100	49¼	115⅜	13000	500	23
					25 CYCLES							
100	40	...	...	...	...	...	...	31½	86¾	4200	120	17
150	60	80	64	44.0	25	...	...	35	86⅞	6200	180	21
275	110	115	90	70.0	80	...	...	43	98⅛	8500	300	28
400	160	150	120	87.5	100	...	...	49¼	115⅜	13000	500	28

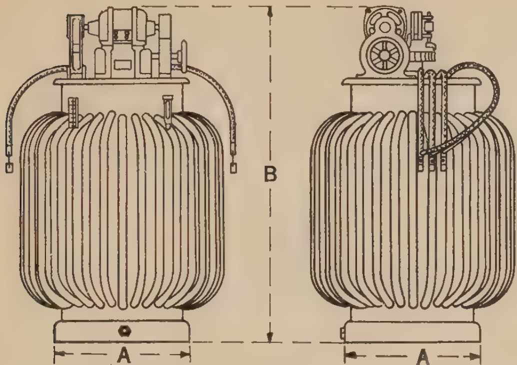


Fig. 92
Dimensions of G-E Three-Phase, 2300-, 4600-, 6600-, 13,200-Volt, 60- and 25-Cycle, Self-Cooled Regulators in Tubular Tank

2300 Volts		4600 Volts		6600 Volts		13,200 Volts		DIMEN. IN IN.		NET WT. in Lb. (Ap-prx.)	NO. OF GAL. OF OIL	TIME OF OPER-ATION in Sec-onds
AMP. of Feed-er	KV-A. of Regu-lator	AMP. of Feed-er	KV-A. of Regu-lator	AMP. of Feed-er	KV-A. of Regu-lator	AMP. of Feed-er	KV-A. of Regu-lator	A	B			
60 CYCLES												
375	150	150	120	88.0	100	. . .	. . .	49¼	92¾	6000	175	17
550	220	235	188	132.0	150	44	100	55	99⅜	8000	300	23
1500	600	450	360	263.0	300	100	228	65¼	118⅞	14000	475	33
2500	1000	1000	800	526.0	600	158	360	71¼	129½	18000	625	35
. . . .	. . . .	. . . .	. . .	. . .	. . .	220	500	84	130	27500	1100	98
25 CYCLES												
250	100	75	60	. . .	. . .	. . .	. . .	49¼	92¾	6000	175	21
375	150	138	110	87.5	100	. . .	. . .	55	99⅝	8000	300	28
625	250	250	200	125.0	140	. . .	. . .	65¼	118⅞	14000	475	40
875	350	375	300	250.0	285	. . .	. . .	71¼	129½	18000	625	42
1325	530	600	480	350.0	300	. . .	. . .	76¼	116	20000	700	54

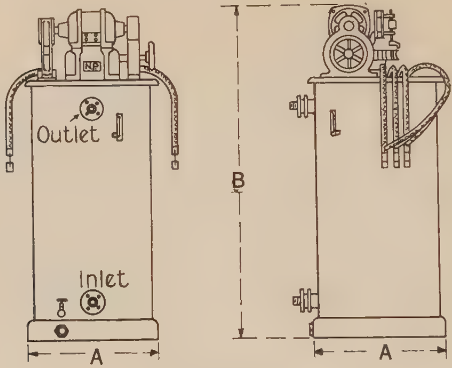


Fig. 93

Dimensions of G-E Three-Phase, 2300-, 4600-, 6600-, 13,200-Volt, 60- and 25-Cycle, Oil- and Water-Cooled Regulators in Boiler Plate Tanks

2300 Volts		4600 Volts		6600 Volts		13,200 Volts		Dimen. in In.		Net Wt. in Lb. (Approx.)	No. of Gal. of Oil	Time of Operation in Seconds
Amp. of Feeder	KV-A. of Regulator	Amp. of Feeder	KV-A. of Regulator	Amp. of Feeder	KV-A. of Regulator	Amp. of Feeder	KV-A. of Regulator	A	B			
					60 CYCLES							
300	120	125	100	65	75	...	...	30	88¼	4000	85	14
600	240	250	200	150	170	...	...	32¾	92¾	5500	125	17
850	340	375	300	228	260	75	170	38¾	99⅜	8000	200	23
1875	750	750	600	440	500	150	340	43¾	118⅞	12000	300	33
3250	1300	1300	1000	800	910	240	550	49½	129½	16000	475	35
4000	1600	1385	1100	835	950	350	800	58	116	25000	525	54
....	....	2500	2000	1500	1700	660	1500	63	130	32000	650	98
					25 CYCLES							
250	100	...	...	...	...	...	...	30	88¼	4000	85	17
375	150	138	110	...	...	...	...	32¾	92¾	5500	125	21
600	240	250	200	150	170	...	...	38¾	99⅜	8000	200	28
900	360	400	320	250	283	...	...	43¾	118⅞	12000	300	40
1300	520	575	460	360	410	...	...	49½	129½	16000	475	42
2000	800	825	660	500	575	...	...	58	116	25000	525	54
....	...	1625	1300	785	900	...	...	63	130	32000	650	98

PART II

REGULATOR AUXILIARIES FOR AUTOMATIC OPERATION

SECTION XIV

THE AUTOMATIC OPERATION OF FEEDER REGULATORS

A modern distributing station may deliver power to a large number of individual feeders each of which requires individual voltage adjustment. One feeder may serve a business district while another from the same bus may serve a residential district, and since the amount of voltage compensation required depends on the load and on the voltage drop in the feeder, and since the peak of the load occurs at different times on different feeders, the automatic regulation of the individual feeder is essential if good regulation is to be obtained on the entire system.

Regardless of the load, the power-factor of the load or the voltage variation on the station bus, any modern motor-operated feeder regulator can be arranged so as to be automatically adjusted for changes in voltage requirements, and the regulator will maintain a constant voltage at any predetermined point on the feeder regulated. It is obviously impossible to obtain these results by the manual operation of the regulators by station attendants even with a single regulator. Hence, to insure a uniform voltage to the consumer and for reasons of economy, the majority of modern regulators are being automatically operated.

The auxiliaries required to control automatically a motor-operated regulator are:

One contact-making voltmeter,
One relay switch,
One potential transformer, and

if the regulator is to compensate for both ohmic and reactive line drop with a variable power-factor load:

One current transformer for single-phase circuits,
Two current transformers for polyphase circuits, and
One line drop compensator.

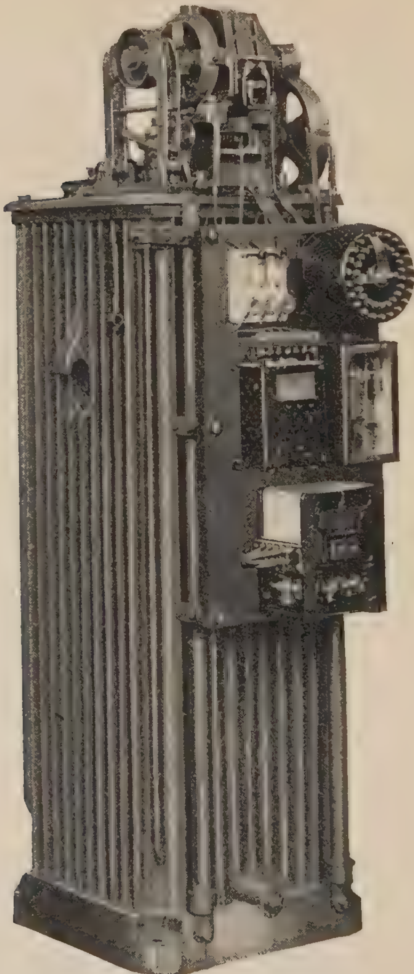


Fig. 94
Single-Phase Regulator with Panel Board

These auxiliaries may be mounted on the switchboard, or, with the exception of the current and potential transformers, on a panel attached to the regulator as shown in Fig. 94. No change whatever is required in the regulator

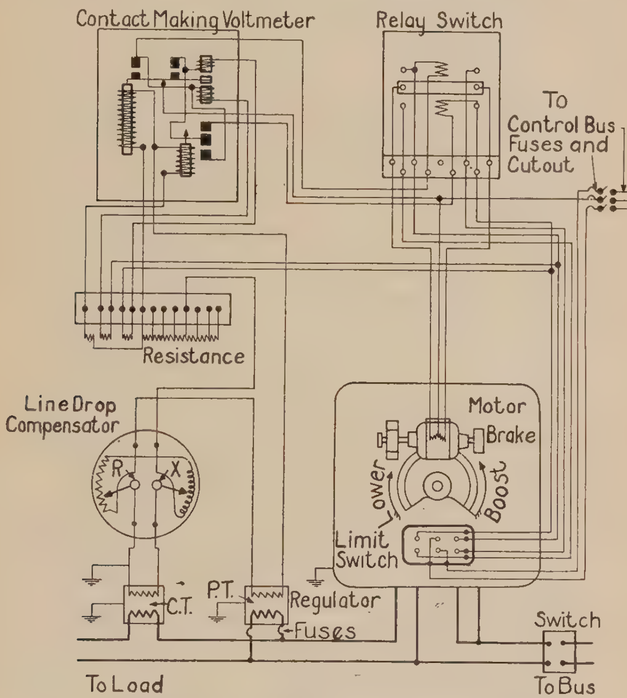


Fig. 95
Wiring Diagram for Single-Phase Regulator Control

itself. The following sections give a detailed description of the design, a detailed explanation of the method of operating, and the dimensions of each device.

The auxiliaries for the control of the single-phase regulator are connected in the circuit as shown in Fig. 95,

and for the control of the three-phase machine as shown in Fig. 96. The contact-making voltmeter is connected through a suitable potential transformer, across the feeder regulated and operates a double-pole double-throw switch,

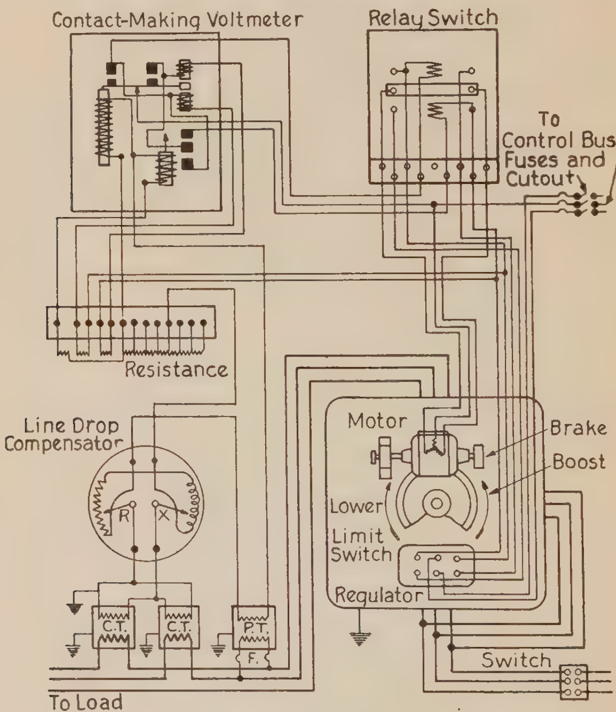


Fig. 96
Wiring Diagram for Polyphase Regulator Control

that is, the relay switch, which in turn controls the operating motor of the regulator. The current transformer is connected in series with the feeder regulated, and its secondary is connected across a variable resistance and reactance designated as the line drop compensator.

Current flowing in the line causes a potential drop across the line drop compensator in which the loss in voltage is dependent on the amount of current in the line. This voltage drop is deducted from the voltage of the potential transformer supplying the contact-making voltmeter, and by this means, any change in the load on the feeder causes an adjustment of the regulator so as to compensate for the corresponding voltage change in the feeder regulated.

The wiring diagrams given show the general arrangement only and should not be used for construction. A detail connection diagram is furnished with every regulator shipped, and only the particular diagram furnished with each regulator should be used for its connection.

SECTION XV

THE CONTACT-MAKING VOLTMETER

The contact-making voltmeter consists primarily of an alternating-current relay so arranged that the moving member is held in a balanced position at any predetermined voltage, that is, normal line voltage. At any given variation in either direction from this voltage, this relay will close an electric control circuit and cause the line voltage, by means of the feeder regulator, again to be brought back to normal. The relay must therefore be connected, across the circuit controlled, on the line side as shown in Figs. 95 and 96. At 100 per cent voltage, the contact-making voltmeter is balanced and the entire control circuit is open. At a lower voltage, a contact is made which will cause the regulator to raise the voltage until it is again normal, at which time the relay will open. In a similar manner, the relay will make a contact to cause the regulator to lower the voltage if it rises above normal.

The satisfactory regulation of the voltage of any circuit by means of an automatic regulator, therefore, depends primarily on the contact-making voltmeter. This device must not only be an instrument of precision and capable of close adjustment but it must also be substantial and reliable, and when once adjusted, must retain its adjustment and require little attention. It must also have enough torque to make a sufficiently good contact for a slight change in voltage so as to avoid sparking and burning of the contact points. At the same time, it must not change in adjustment due to the change in the frequency of the circuit caused by slight changes in the speed of the generator.

This combination seemed exceedingly difficult to obtain in an alternating-current device of simple design,

and the first contact voltmeter developed by the General Electric Company, about 1902, was in the form of the Thomson balance. One design of this form of voltmeter arranged with holding coils and a dashpot is shown in

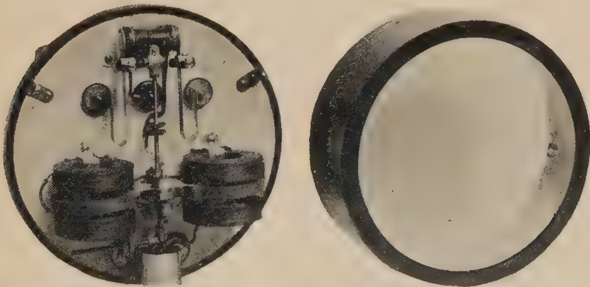


Fig. 97
110-Volt, 60-Cycle Potential Relay

Fig. 97. This design was sufficiently accurate but was slow in operation, and it was only after considerable experimental and developmental work had been done that the present form of meter consisting of a solenoid and a light-weight open magnetic circuit core was adopted. This meter is, in effect, the alternating-current voltage element of the generator voltage regulator.

The use of the iron core, while increasing the torque and sensitiveness, introduces frequency errors, to compensate for which it is necessary to use a relatively large ohmic resistance in series with the coil. The larger the ohmic resistance in proportion to the reactive resistance, the less this error becomes. The combination used in a standard relay for 110 volts and 60 cycles is about 280 ohms resistance and 35 ohms reactance. This combination reduces the frequency error to 0.04 per cent in voltage for each 1.0 per cent change in frequency from normal. The original

design of this relay is shown in Fig. 98 and the diagram of connections in Fig. 99.

Compensation by Series Winding

In addition to the shunt winding excited from the regulated side of the feeder controlled, the earlier relays were also arranged with an adjustable winding in series with the secondary of the series transformer connected in this feeder. This series winding was connected so that the current from the series transformer was opposed to that in the shunt winding. With no load on the feeder, the relay was adjusted so that it would be balanced at the voltage required at the load. With full load on the feeder, the series winding of the relay was adjusted by means of the dial switches shown, so that the voltage on the feeder at the load was again normal. The bucking effect of the load current through the series transformer neutralized part of the pull of the shunt coil. The relay then indicated low-voltage and caused the regulator to boost until a balance was again obtained. The voltage of the feeder at the station was therefore higher than normal, but by properly adjusting the dials of the series winding, the voltage at the center of distribution was maintained at normal; that is, the series winding was adjustable so as just to compensate for the voltage drop in the feeder.

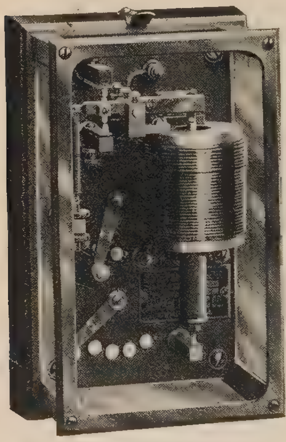


Fig. 98
Type TS Contact-Making Voltmeter for Induction Voltage Regulator

Under certain conditions, this adjustment held for all loads, so that after the compensation of the contact-making voltmeter had been properly adjusted for a certain feeder,

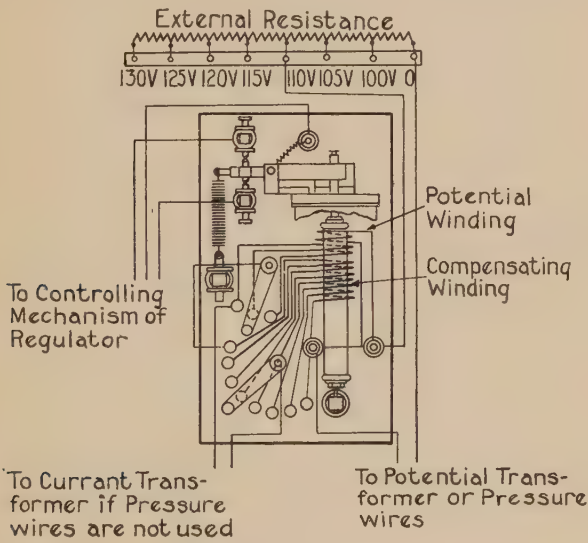


Fig. 99
Connections of Form B Contact-Making Voltmeters

the regulating equipment would automatically maintain a constant voltage at the load and for all loads, and would require no further attention.

This simple design of relay was satisfactory for controlling a non-inductive load or one of a constant power-factor, as, for instance, incandescent lighting, but was unsuitable for mixed lighting and power loads. With a non-inductive load, the phase angle between the currents in the shunt and series windings was approximately zero, and with a load of constant power-factor, this angle was

fixed and so a single adjustment of the series winding answered for all line currents. However, if the load was of varying power-factor, the compensation depended not

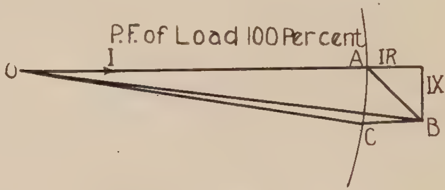


Fig. 100
Vector Diagram of Contact-Making Voltmeter with Compound Winding

only on the current flowing in the series winding, but also on its phase angle with reference to the current in the shunt winding. This can best be illustrated by diagrams as shown in Figs. 100 and 101.

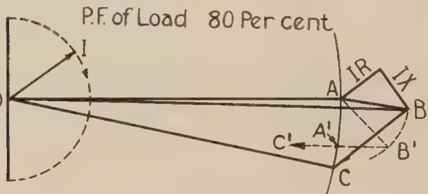


Fig. 101
Vector Diagram of Contact-Making Voltmeter with Compound Winding

The core of the contact-making voltmeter is maintained in its neutral position by the ampere-turns of the shunt winding with 100 per cent voltage applied to the terminals of this winding and without any current in the series winding, or by any combination of the ampere-turns of both windings equal to this amount.

As the shunt coil of the meter with its resistance is practically non-inductive, it may be assumed that the current in this coil is always in phase with the regulated

feeder voltage regardless of the load or the power-factor of the load on the feeder, and that the shunt ampere-turns are directly proportional to this voltage. The current in the series coil is, however, in phase with the load current and its phase relation to the shunt current depends on the power-factor of the load.

Voltage Drop in Feeder

The voltage drop in a feeder is due to both ohmic and inductive resistance, the former of which is in phase with and the latter at right angles to the line current. As the power-factor of the line varies, the direction of this voltage drop varies and in value depends on the current flowing in the feeder. In Figs. 100 and 101, it is assumed that full-load current flows and that the ohmic and the reactive voltage drops are equal.

Fig. 100 illustrates the conditions with 100 per cent power-factor load. In the illustration, OA represents the load voltage and OI the load current. IR is the resistance drop of the feeder in phase with the current and IX the reactance drop at right angles to it. The total line drop is then AB and at an angle to the load voltage as shown. The station voltage must therefore be OB; that is, due to the reactance of the line it must be greater than $(OA+IR)$ and at an angle BOA to the current.

For the contact-making voltmeter, OA may represent the ampere-turns of the shunt winding required to obtain a balance, that is, due to 100 per cent voltage at no load. As shown, however, in order to obtain this voltage at the load with full-load current flowing in the line, the voltage at the station must be OB which under the load condition given must now represent the ampere-turns of the shunt winding of the meter in both direction and value. To

maintain a balance of the meter, this value of OB must therefore be partly neutralized by the series winding, that is, until an effective value equal to OA is again obtained.

The current in the series winding is in phase with OI, and the resultant of the series ampere-turns and the shunt ampere-turns OB must equal OA. Therefore, the intersection of the arc, having O as a center and OA as a radius, with the line drawn from B and in phase with OI, determines the required ampere-turns of the series winding, that is, BC represents in value and in direction the series ampere-turns for which the series winding of the contact-making voltmeter must be adjusted in order to provide correct voltage compensation for the condition given.

Fig. 101 represents the condition of the same line and contact-making voltmeter with an 80 per cent power-factor load on the line. It should be noted that, due to the lower power-factor of the load and, hence, the lag in the current OI behind the load voltage OA, the amount of compensation required of the series ampere-turns must be considerably increased in order to obtain the same results as in the previous case. In other words, BC in Fig. 101 is greater than in Fig. 100.

As with a given power-factor load the line drop (both ohmic and reactive) varies in value directly with the load but is fixed in direction, it is obvious that the compensation obtainable by a given adjustment of the series winding is correct for all loads. A comparison of the two diagrams will show, however, that the compensation is incorrect if the power-factor of the load changes. The error increases as the power-factor decreases.

In Fig. 100, which gives the conditions at 100 per cent power-factor, the series compensation CB is practically equal to the resistance drop IR, and a slight change in the

power-factor of the load will not appreciably change the required compensation, so that for all practical purposes, a single adjustment of the compensation is satisfactory even if the power-factor of the load varies slightly, provided however, that the power-factor is near 100 per cent.

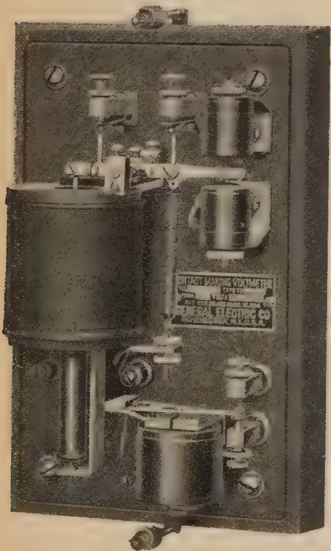


Fig. 102
Type TS Form B7 Contact-Making Voltmeter

In Fig. 101, which gives the conditions at 80 per cent power-factor, the series compensation is, however, much greater, and if the load should change to 100 per cent power-factor, B would rotate to B' as in Fig. 100 and CB would assume the position $C'B'$ parallel to the 100 per cent power-factor current, resulting in an over-compensation nearly equal to $C'A'$ in Fig. 101. Stated otherwise, the load voltage would be increased by this amount instead of being maintained constant.

Compensation by Line Drop Compensator

The tendency in the distribution of power is toward mixed lighting and motor loads, so that the method of line drop compensation described is nolonger generally suitable. To satisfy all conditions of load with a single set of standardized auxiliaries, a compensating device designated as the "Line Drop Compensator" (and hereinafter described) has

therefore been provided external to the contact-making voltmeter, and in the modern meter, the series winding compensating feature is omitted.

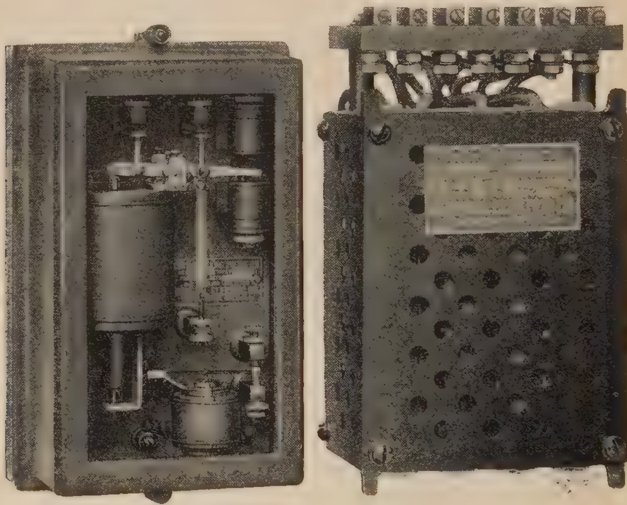


Fig. 103
Type TS Form B7 Contact-Making Voltmeter and Resistance Box

This design of meter is shown in Fig. 102, and complete with its non-inductive resistance, in Fig. 103. The diagram of connections is given in Fig. 104. The outline giving all overall dimensions and the drilling plan is shown in Fig. 105.

As operating conditions required, a number of designs intermediate between those shown in Figs. 98 and 102 were made. When automatic regulators were first introduced, they controlled feeders limited almost entirely to lighting. The load was fairly steady and without fluctuations. The only requirement of the regulator was to increase the voltage gradually as the load was increased

and again to lower it with a decreasing load. In some cases, the regulator operated from lower to boost and back to lower only once a day.

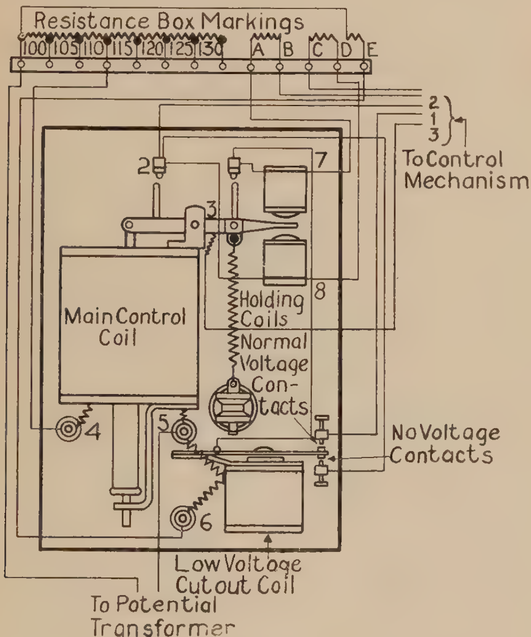


Fig. 104
Connections of Type TS Form B7 Contact-Making Voltmeter

When, however, motors were connected to the lighting circuits, the voltage dropped with each starting of a motor. As the motors usually came up to speed in less time than that required for the regulator to compensate for the drop caused by the starting of the motor, and since it was undesirable to attempt to compensate for these short time changes in voltage, a dashpot was added to the moving

core of the contact-making voltmeter so as to prevent an immediate response to these voltage changes. The dashpot did not interfere with the correction of voltage variations covering a longer period of time.

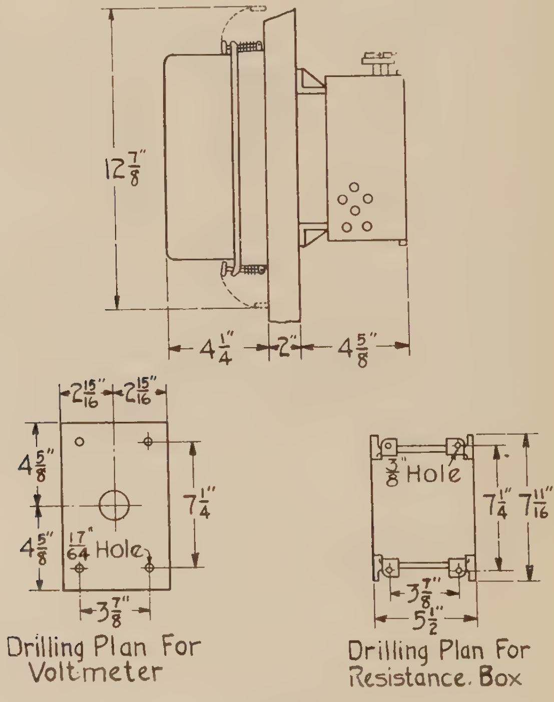


Fig. 105
Dimensions of Contact-Making Voltmeter

It was not long, however, after the introduction of automatic feeder voltage regulation that the users of incandescent lamps demanded better service and quicker correction of voltage variations. This demand resulted in the development of a much quicker operating regulator and

a corresponding change in the contact-making voltmeter. The change consisted in the elimination of the dashpot which retarded the action of the relay, and the re-adoption of the holding coils which accelerated this action and made it more positive.

Holding Coils

The holding coils are connected across the relay contacts so that, as soon as even a slight contact is made, the proper holding coil is energized and holds the contacts firmly together. The operation is as follows:

With the feeder at normal voltage, the lever arm of the relay is in a horizontal position with neither contact closed. A predetermined variation in voltage either above or below normal causes the closing of one or the other of the contacts and thereby energizes, not only the relay switch which starts the motor, but also one of the holding coils as well. The energizing of the holding coil holds the contacts of the meter firmly together and thus causes the regulator to operate and adjust the voltage until normal line potential is again nearly attained, after which the relay opens.

Assuming that the normal line voltage is 100 per cent and that the adjustment of the regulator equipment is such as to maintain this voltage within 1 per cent either way from normal, then, as soon as the voltage reaches 101 per cent, one of the contacts of the contact-making voltmeter closes and the corresponding holding coil causes a firm contact to be made and causes the relay switch to close. The regulator then lowers the line voltage, but as soon as this voltage has reached 100.5 per cent, the contact-making voltmeter opens the relay switch circuit. In other words, the holding coil holds the contact closed while the voltage varies from 101 to 100.5 per cent. The same procedure

follows the lowering of the line voltage, for as soon as the voltage reaches 99 per cent, the boosting contact of the contact-making voltmeter closes and the opposite holding coil keeps the contact closed until the line voltage reaches 99.5 per cent at which voltage the meter, and hence the relay, opens the control circuit.

The operating motor once started does not, however, stop at the instant it is disconnected from the circuit by the relay switch but it continues to rotate, due to its inertia, until brought to rest by its load. The permanent brake on the motor shaft is therefore so adjusted by the tension spring, or the magnetic brake so adjusted by its weight, that the motor overruns a sufficient amount to produce a further change in voltage of about 0.5 per cent, or just enough to bring the line potential back to normal. This feature of the contact-making voltmeter causes the line voltage to be returned to normal, prevents intermittent contact of the meter and of the relay switch, and hence greatly reduces the number of operations of the control and regulating mechanism.

No-Voltage Cutout

A no-voltage cutout is incorporated in the new contact-making voltmeter. Its function is to cause the regulator to assume the minimum voltage position in case the voltage of the feeder should, for any reason, fail. The operating motor and relay switch are usually connected to the station supply bus which is independent of the feeder controlled. The opening of the feeder switch or circuit breaker, or the lowering of the voltage of a feeder due to a short circuit, normally allows the armature of the contact-making voltmeter to drop, as in low voltage, and, therefore, causes the regulator to be moved to the maximum boost position

so that when the circuit is again restored it will be in its maximum voltage position.

It is preferable, however, especially when low voltage occurs due to a short circuit, that under these conditions the voltage should be a minimum when a circuit is restored, and the no-voltage cutout is provided to produce this result. This cutout consists of a solenoid and core, and is connected across the feeder controlled. At voltages between 50 and 100 per cent of normal, the weight of the core is supported by the pull of the coil, and the contact-making voltmeter connection is as described. If the voltage fails or drops to below 50 per cent of normal, the armature of the cutout drops, and by its weight, reverses the contact connections of the contact-making voltmeter. This causes the regulator to rotate to the maximum lowering position with the contact-making voltmeter in the low-voltage position. As soon as the circuit is restored, the armature of the cutout is again raised and the action of the regulating mechanism is again normal. The operation of the cutout is entirely automatic and requires no attention or adjustment.

Mechanical Design

In view of the importance of the contact-making voltmeter in the automatic regulation of voltage, special care is taken in its design, manufacture, adjustment, and test. It is of substantial construction; the moving element is made as light as possible (the arm is of aluminum); the pivot bearings are carefully hardened and polished; and the main contacts are of iridium-platinum, a combination which is less subject to wear and oxidation than any other substance known. The mechanism of the instrument is covered with a dustproof glass front cover which can,

however, be readily removed if occasion should require. All adjusting parts are readily accessible, and after adjusting, require no further attention other than an occasional cleaning of the main contacts. That cleaning is, however, seldom required is indicated by the satisfactory operation of these instruments for long periods of time without any attention whatever.

The instrument is intended for switchboard mounting and the resistance used in series with the main coil is arranged to be mounted on the back of the board, and held with the same bolts as the relay itself, in the manner shown in Fig. 105.

Adjustment of Contact-Making Voltmeter

Automatic regulators are usually adjusted to maintain the voltage constant within 1 per cent either way from normal. The ability of the voltage regulating apparatus to maintain this regulation depends, however, on the causes of the voltage variation and on the nature of the generating and distributing system. The closing of a switch to connect a lamp load or a motor load to the feeder causes a practically instantaneous voltage drop which cannot be immediately compensated for by any form of regulator with moving parts because of the inertia of those parts

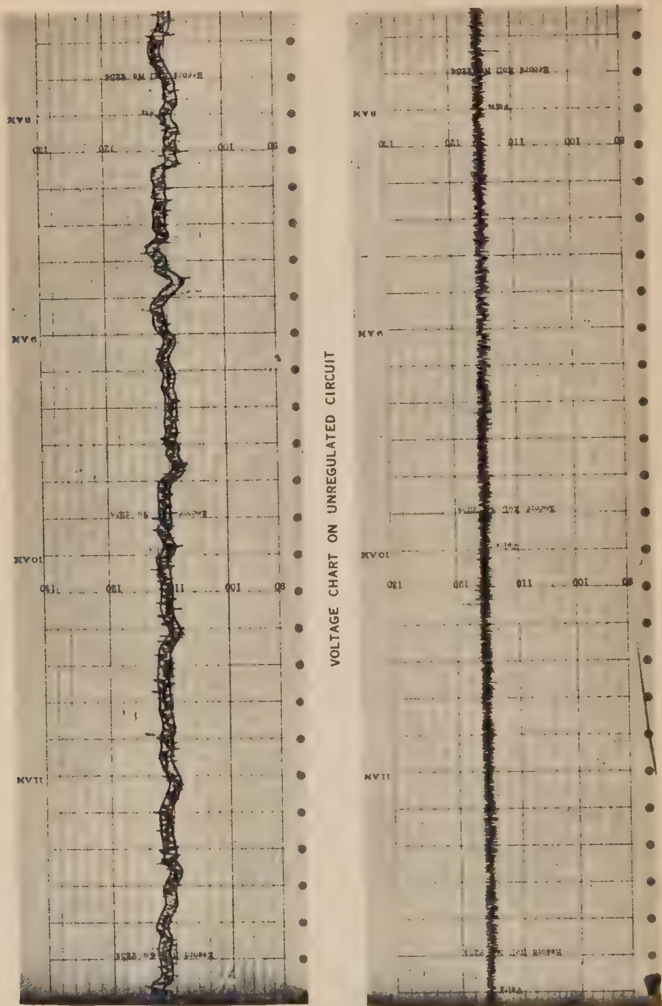
As several successive operations are required in the regulator (such as the making of the contact in the contact-making voltmeter and the closing of the relay switch followed by the starting of the motor) before the regulator can start to compensate for a voltage change, sufficient time may elapse for the voltage to return nearly to normal (as in the case of the starting of an induction motor) before the regulator responds to the initial voltage change. Circuits subject to sudden changes can not

therefore, be maintained at a constant and uniform voltage, but can be maintained at any predetermined voltage for any condition of load which is maintained for a sufficient length of time for the regulator to act and which is within the voltage range for which the regulator was designed.

Intermittent Voltage Fluctuations

Feeder circuits may also be subject to constant and practically instantaneous voltage fluctuation as shown in Fig. 106. These fluctuations may average only a fraction of 1 volt or they may extend over as much as 3 or 4 volts. By means of a regulator, the average voltage may be corrected as shown, but the regulator can not reduce the width between the two parallel lines drawn through the average maximum and minimum voltage fluctuations regardless of the equivalent of this width in volts.

If, therefore, a circuit is subject to such voltage oscillations, the contact-making voltmeter should not be adjusted for any closer voltage regulation than represented by the average maximum intermittent voltage variations as illustrated in Fig. 106. Such fluctuations are, in general, greater in low-frequency circuits, and in some 25-cycle systems, the variation may be as high as 4 per cent. In this particular case, the regulator should be adjusted to maintain a given voltage not closer than 2 per cent either way from normal. Otherwise, the operation of the regulator will be continuous, and this will result in an increase in the wear of the mechanism with a corresponding decrease in its life, also an increase in the attention required and, hence, in the cost of upkeep, without any compensating results.



VOLTAGE CHART ON REGULATED CIRCUIT (IRS REGULATOR)

Fig. 106 Chart Showing Regulation of Voltage by a Type IRS Regulator

As indicated in Figs. 103 and 104, the series resistance is arranged with a number of taps so that any standard meter can be used on circuits of different voltage regulation requirements. Resistances have been standardized for use on 110- and 220-volt circuits. Those for the former have a range of from 100 to 130 volts in 5-volt steps, and those for the latter, of from 200 to 260 volts in 10-volt steps.

The main adjustment of the meter should be obtained by selecting the proper tap of the resistance as indicated in Fig. 104, and the final adjustment effected by means of the tension spring used as a counterbalance for the core. The holding coils are adjusted at the factory for 0.5 volt but can readily be readjusted by means of thumbscrews. The no-voltage cutout requires no adjustment.

SECTION XVI
THE RELAY SWITCH

The relay switch consists of a double-pole double-throw switch operated by two alternating-current magnets controlled by the contact-making voltmeter. Two designs of this switch have been developed and standardized. Each design is best adapted for the application for which it is intended.

The design heretofore most commonly used is the so-called pendulum type. It is absolutely quiet in its operation, and is therefore best adapted for use in substations containing no rotating or moving apparatus, or wherever noise of any character is objectionable.

The second design, designated as the contactor type, requires less attention in that the contacts do not require so frequent cleaning or renewal as in the former design, but it is more or less noisy in its operation. It is therefore applicable to situations where noise is not objectionable and is particularly desirable for use with regulators installed on poles or in out-of-the-way locations where the less frequent attention required by this design of switch may be of considerable value. Both designs are briefly described and illustrated in the following.

Pendulum Type

The standard form of the pendulum type is shown in Fig. 107. The magnet cores, built up of **E**-shaped laminated sheet iron, are supported in non-magnetic frames, and a common armature is pivoted between them. The moving element of the switch is suspended from this armature so that, when the excitation of either magnet attracts the armature, the switch is caused to close on one side or the other depending upon which magnet is excited. The opening of the circuit causes the switch to open by gravity and by means of springs which accelerate the movement.

The magnet cores are arranged at an angle so that, when the switch is closed on either side, the face of the armature is parallel with that of the core. This reduces to a minimum the energizing current which must be handled

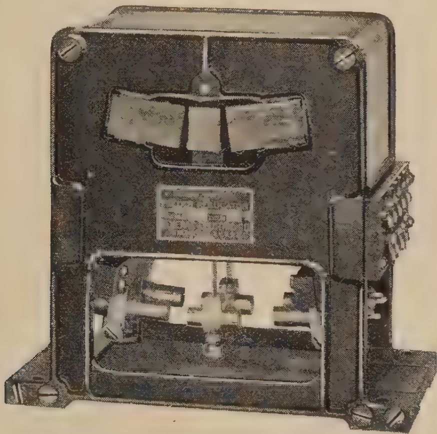


Fig. 107
Form A7 Relay Switch

by the contact-making voltmeter contacts. By means of a thin non-magnetic metal shim, the two surfaces are prevented from coming into actual contact. This eliminates any tendency to stick due to residual magnetism. A spring, arranged between the frames, exerts a minimum pressure on the top of the armature with the switch in the open position. As the armature swings to either maximum position, the pressure of this spring increases. The moving contacts are supported on springs which are in tension when the armature is in either maximum position, so that as soon as the energizing current is broken, the pressure of the spring on top of the armature, as well as the pressure

of the springs on which the contacts are mounted, accelerates the opening of the switch, and gravity holds it in the open position.

The moving contacts are of brass and the stationary ones are of graphitized carbon. This combination has been found to be ideal as these contacts will not stick or freeze. Graphitized carbon is very uniform in structure so that it wears evenly, requires less attention, and has a much longer life than other forms of carbon or graphite.

The carbon contacts are adjustable by means of threaded holders with thumbscrew attachments. Thus the wear may be taken up as occasion requires. In making the adjustment, the contacts should be adjusted ⅛ inch beyond the extreme positions of the movable contact. The cover of the switch is removable, and a terminal board is provided to facilitate the making of connections.

Fig. 108
Automatically Operated Single-Phase Regulator with Relay Switch Mounted on Cover

This switch may be mounted in any convenient location where it is accessible. It may be mounted on

brackets back of the switchboard or arranged for mounting directly on the front of the board or even on top of the regulator itself as shown in Fig. 108. The contacts will require occasional attention the same as any other contact-

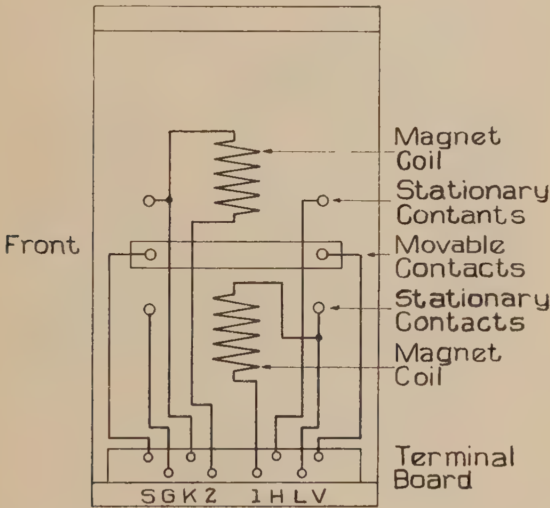


Fig. 109
Connections of Pendulum Type (Form A7) Relay Switch

making and breaking device. The amount of this attention will depend on the service required of the regulator.

The diagram of connections is given in Fig. 109 and the overall dimensions in Fig. 110. As indicated in the dimension diagram, two sizes of this design of relay switch have been standardized. The smaller size is suitable for motors requiring a starting current up to 20 amperes at either 110 or 220 volts, and the larger size is suitable for motors requiring a starting current of twice this amount.

Under some conditions of line voltage regulation, the operation of the regulator is practically continuous. Hence, it is highly desirable that the various currents made and broken by the auxiliaries be as small as possible so as to

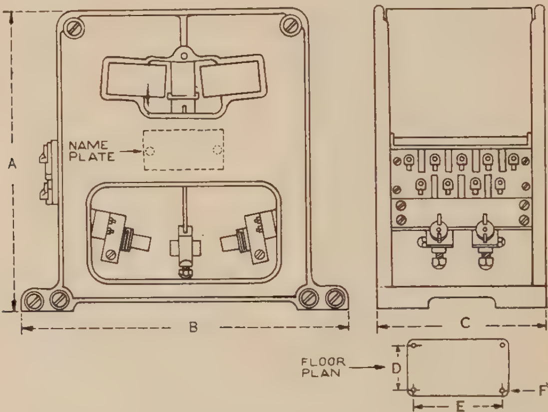


Fig. 110
Dimensions of Pendulum Type (Form A7) Relay Switch

SIZE		DIMENSIONS IN INCHES						NET WT. in Lb. (Apprx.)
Amp.	Volts	A	B	C	D	E	F	
20	110/220	9 1/16	9 3/4	5	4 1/4	8 1/4	5/16	18
40	110/220	11 3/8	12 1/2	6 25/32	5 17/32	10 5/8	11/32	40

reduce the cost of upkeep. The relay switch magnets are designed with this in view, and the current required by the smaller relay and handled by the contact-making voltmeter is only 0.12 ampere with the switch open and 0.06 ampere with the switch closed when energized at 110 volts. The larger relay requires about twice this current for satisfactory operation. As the motor current made and

broken by the relay switch is of considerable magnitude compared with the current required to operate the relay, it is of still greater importance to have the motor current as small as possible, and it is recommended that the

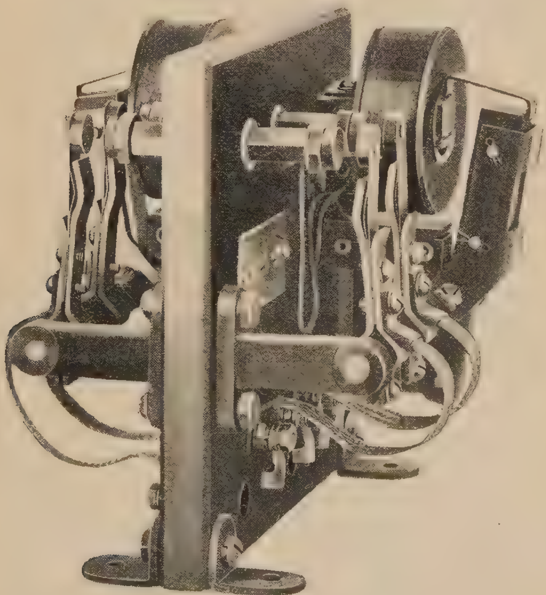


Fig. 111
Form D101 Relay Switch

operating motors, especially the larger sizes, be always arranged for 220-volt excitation.

As has previously been stated, the contacts of the contact-making voltmeter require very little attention, but those on the relay switch require adjustment and renewal, depending upon the size of the regulator controlled and upon the requirements of regulation. It is therefore

important that the relay switch contacts be given systematic attention and that, in replacing them, the materials called for on the instructions pasted on the relay switch cover be used, and not the ordinary arc light graphite or carbon.

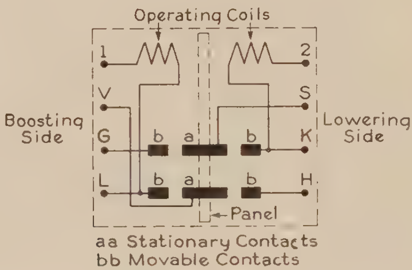


Fig. 112
Connections of Contactor Type (Form D101) Relay Switch

Contactor Type

The contactor type design of relay, as its name implies, consists of the well-known contactor type of switch. Two contactors are mounted back to back on a panel as shown in Fig. 111 and are mechanically interconnected so that both contactors cannot be closed simultaneously. The relay may be mounted on a vertical or horizontal support. All parts are accessible and the contacts are readily renewable. Both contacts are of metal and require a quick motion and a heavy pressure to prevent burning and sticking. This quick action causes the noisy operation, but it also increases the life of the contacts. The relay shown is designed for a 25-amp. circuit and the switch will make and break this current, at 110 or 220 volts, approximately one million times before requiring a renewal of the contacts. A diagram of connections is shown in Fig. 112, and the outline in Fig. 113.

This design of relay, but of a larger size, has been used during the last 15 years in the automatic control of the larger sizes of induction regulators, and aside from the noisy operation has given general satisfaction. Its

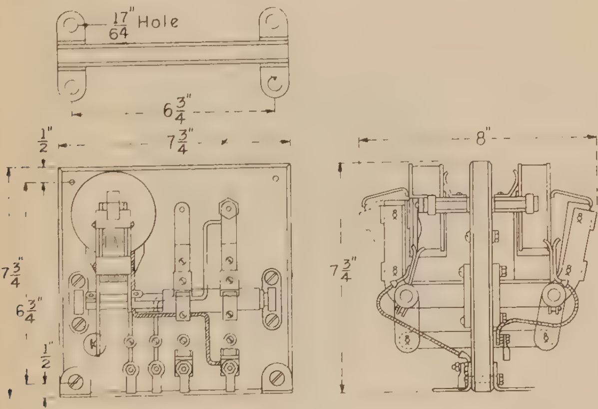


Fig. 113
Dimensions of Contactor Type (Form D101) Relay Switch

application has more recently also been extended to the control of all sizes of regulators, and because of its reliability and the small amount of attention required, it will undoubtedly supersede the pendulum type except in such instances where a minimum of noise in the station is essential.

SECTION XVII

THE LINE DROP COMPENSATOR

The line drop compensator consists of a variable resistance and reactance (each independently adjustable) by means of which, when used with an automatically

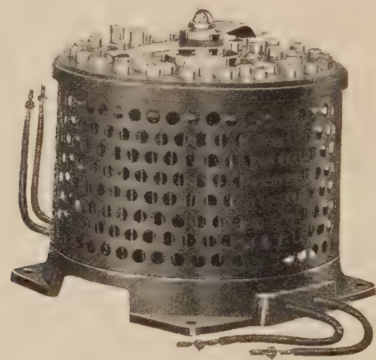


Fig. 114
Line Drop Compensator

controlled feeder voltage regulator, correct line drop compensation can be obtained at some predetermined point on the feeder regulated regardless of the load or the power-factor of the load on the feeder, provided, however, that the load is taken from the feeder at or beyond the point at which constant voltage is to be maintained.

The standard design of compensator is shown in Fig. 114 and the diagram of connections, with reference to the line, in Fig. 115. As indicated in Fig. 115, the compensator is connected in series with the secondary of a series transformer the primary of which is in series with the regulated feeder. The compensator also is in series with the secondary of the potential transformer which excites the contact-

making voltmeter, the primary of which transformer is connected across the feeder regulated.

The resistance and the reactance of the compensator are each divided into a number of equal sections. Taps

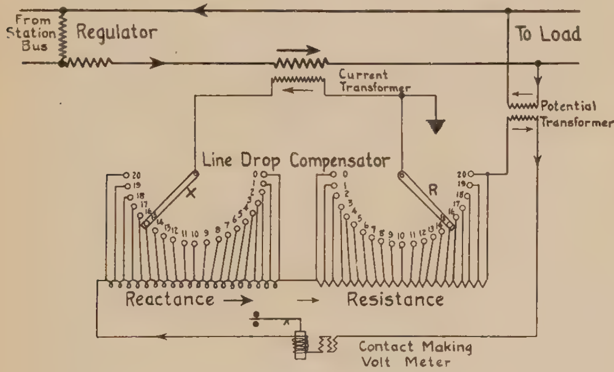


Fig. 115
Connections of Line Drop Compensator

are brought out from these sections and connected consecutively to independently adjustable dial switches. The entire resistance and reactance is connected permanently in series with the potential transformer and the contact-making voltmeter, but the resistance and reactance of the compensator connected in series with the current transformer is adjustable by means of the dial switches as shown.

As connected, any current flowing in the line is reproduced in the compensator in the inverse ratio of the current transformer windings and produces a potential drop equal to the voltage across the current transformer terminals, that is, between the regulating arms of the dial switches of the compensator. This voltage is directly proportional to the

line current flowing and to the percentage of the resistance and the reactance of the compensator in series with the current transformer. The current and potential transformers are so connected that the currents from both are in the same direction in the line drop compensator as illustrated in Fig. 115.

The current flowing in the contact-making voltmeter produces a definite and constant voltage drop in the line drop compensator. The contact-making voltmeter is adjusted to compensate for this drop by means of the variable resistance in series and by means of the adjusting spring. The current from the current transformer produces an additional voltage drop. This voltage drop depends on the adjustment of the line drop compensator and on the line current flowing. This voltage drop in the compensator due to the current obtained from the current transformer reduces the voltage obtained from the potential transformer and applied to the contact-making voltmeter coil Any discrepancy from normal in the voltage across the contact-making voltmeter causes the regulator to operate in such a manner as to bring it back to normal. Hence, the voltage across the compensator is adjusted so as to be directly proportional to the voltage drop in the feeder.

With no current flowing in the line, the voltage drop across the compensator normally due to load is zero and the full voltage of the potential transformer is applied to the contact-making voltmeter. The contact-making voltmeter causes the regulator to maintain a constant and predetermined voltage across the terminals of the contact-making voltmeter. At this voltage, the balance arm of the contact-making voltmeter is in the mid-position. With no load on the feeder, the voltage across the feeder is uniform and constant throughout its entire length.

With current flowing in the line, the voltage drop across the compensator is, however, deducted from the voltage of the potential transformer which supplies the contact-making voltmeter, and as the contact-making voltmeter requires a constant voltage to maintain its balance, it causes the regulator to raise the voltage until the difference in the voltage between the potential transformer and the voltage drop across the compensator (that is, the voltage across the contact-making voltmeter) is again as before.

In other words, the voltage across the primary of the potential transformer will be higher than before, but, at some point on the feeder, at which point the voltage drop due to the load is proportional to the voltage drop across the compensator, the voltage will be that for which the meter is adjusted. Constant voltage can be maintained at any one predetermined point on the feeder by adjusting the voltage drop across the compensator in proportion to the voltage drop in that portion of the feeder which is between the regulator and the point on the feeder considered.

As stated in Section XV, the voltage drop in the feeder is due to both the ohmic and inductive resistance of the feeder. The voltage drop due to the former is in phase with, and the voltage drop due to the latter at right angles to, the current flowing. Also, the voltage drop with reference to the station voltage depends on the angle between the current and the voltage, that is, on the power-factor of the load. To obtain correct line drop compensation, this compensation must therefore not only be in direct proportion to the load, as is obtained by means of the compound winding of the contact-making voltmeter, but it must also vary in its angular position to the station

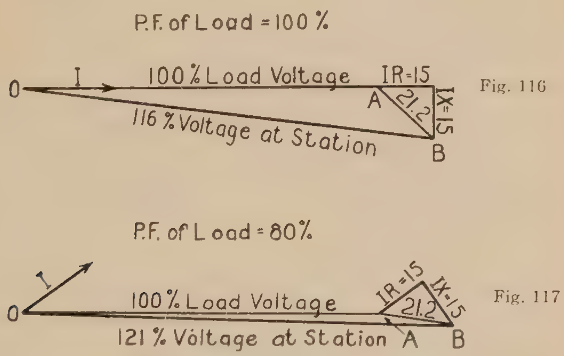
voltage as the line current varies. This requirement is satisfied by a proper combination of resistance and reactance in the compensator, for, as the current in the secondary of the current transformer (and, hence, this current in the compensator) is always in phase with the line current, the voltage drop across the compensator is always in the same angular relation to the station voltage as the voltage drop in the line due to the line current, provided the resistance and the reactance of the compensator are each proportional to the resistance and the reactance of the line. Under this condition, the voltage drop across the compensator is always in phase with the voltage drop in the line and proportional to it.

The angular relation between the line current and the voltage drop across the compensator is constant for any given adjustment of the compensator regardless of the power-factor of the load on the line; but, in their angular relation to the line voltage, both vary with the power-factor. With the line drop compensator properly adjusted and connected as shown, the contact-making voltmeter circuit is, in effect, a miniature duplication of the line. The voltage drop across the compensator varies in value directly with the line current flowing, and in direction, with the angle between the line current and voltage, that is, it varies with the power-factor of the load.

The relations between the values and directions of the various voltages and for loads of various power-factors can be illustrated by diagrams. Fig. 116 represents the relations for 100 per cent power-factor and Fig. 117 may represent these relations for any other power-factor load.

For illustration, it will be convenient to assume a single-phase 2200-volt 100-amp. feeder, having an ohmic and reactive voltage drop of 15 per cent each when

full-load current is flowing, and that the low-voltage distribution is at 110 volts. Then for this condition, the current transformer will have a ratio of 20 to 1, that is, 100 amperes in the line will cause 5 amperes to flow through

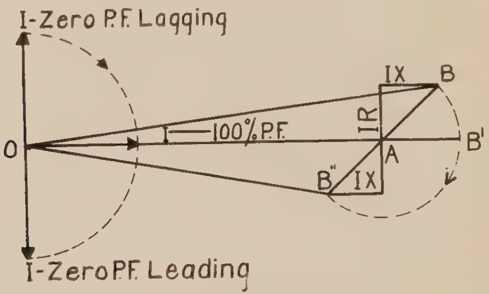


Figs. 116 and 117
Vector Diagrams Showing Effect of Line Drop Compensation

the compensator. The potential transformer also will have a ratio of 20 to 1, so that 2200 volts impressed across the primary will give 110 volts on the meter, which is also the voltage required for distribution. With this arrangement, the voltage across the contact-making voltmeter will be the same as that required at the load, and the percentage voltage drop in the 2200-volt line when referred to the distributing voltage will be identical to the percentage voltage drop in the contact-making voltmeter circuit when the compensator is adjusted for 15 per cent ohmic and 15 per cent reactive drop, which corresponds to the percentage voltage drop in the line.

Figs. 116 and 117 therefore represent both the conditions in the line and those in the contact-making voltmeter circuit. The *IR* drop is in phase with the current *I*

regardless of the phase angle of this current with the voltage, and the IX drop is at right angles to it. The total voltage drop is AB which, for the conditions assumed, is 21.2 per cent of the load voltage. For the line constants



I = 100% Current, IX = 15%, IR = 15%
OA = Volts at Load and Meter = 100%
AB = Volts across Compensator = 21.2%
OB, B', B'' Volts at Station End of Regulator
at Zero Power-Factor Load Lagging OB = 116
at 80% Power-Factor Load Lagging OB = 121
at 100% Power-Factor Load Lagging OB = 116
at Zero Power-Factor Load Leading OB = 86

Fig. 118

General Vector Diagram of Line Drop Compensation Obtainable by the Use of a Line Drop Compensator

assumed, this value depends only on the value of the line current and is directly proportional thereto, and its direction depends on the direction of the line current.

The voltage required at the station to maintain a constant voltage at the load for loads of different power-factors therefore also depends on the power-factor. For instance, with a 100 per cent power-factor load, the regulated voltage at the station is 116 per cent, whereas with an 80 per cent power-factor load, this voltage is 121 per cent of the load voltage. Fig. 118 shows the values of the voltages required at the station to maintain a constant

voltage at the load for 100 per cent current and loads of power-factors from zero leading to zero lagging. It should be noted that the voltage drop across the compensator is constant for a given value of load current and that the angular relation between this voltage drop and the line current is constant but that the voltage at the station varies for different power-factors.

Since the diagrams show that the contact-making voltmeter circuit exactly duplicates line conditions, it follows that a voltage-regulating equipment, arranged as indicated and properly adjusted, will maintain constant voltage at any predetermined point on the line regardless of the load or the power-factor of the load.

Correct compensation can likewise be obtained by connecting the resistance and reactance of the compensator permanently in series with the current transformer and varying the connection across the potential transformer circuit. This arrangement is not, however, so convenient as the one shown and standardized, for the reason that the resistance and the reactance values of the compensator are so high, compared with the resistance and the reactance of the contact-making voltmeter and its resistance, that any change in the adjustment of the compensator changes the current in the meter and therefore requires its readjustment. By connecting the compensator as recommended, the total resistance and reactance in the contact-making voltmeter circuit remains constant. As a result, the current in the meter, and hence its adjustment, remains constant regardless of the adjustment of the compensator.

If desired, an indicating voltmeter can be connected in parallel with the contact-making voltmeter and its resistance. The indicating meter will show the approximate voltage at the center of distribution of the feeder for which

the compensator is adjusted. The voltage indicated will, however, always be slightly lower than at the load, by an amount equal to the voltage drop in the compensator due to the indicating voltmeter current, unless the indicating instrument is recalibrated. This discrepancy is, however, constant and independent of the load, and is generally less than 2 volts. The smaller the current taken by the indicating meter, the less the error will be.

The voltage drop caused by the indicating instrument likewise affects the contact-making voltmeter circuit so that loading the circuit with the indicating instrument requires a readjustment of the contact-making voltmeter. By making the required adjustments in the instruments, this arrangement thus allows the use of any standard indicating voltmeter and dispenses with the special line drop compensator heretofore used, and simplifies the installation to this extent.

Grounding of Current and Potential Transformers

It is a general practice to ground both current and potential transformers, but feeders controlled by regulators equipped with line drop compensators do not require the grounding of both transformers. As a matter of fact, such grounding is prohibitive with the connections shown in Fig. 115 as it short circuits a part of the line drop compensator. Grounding the current transformer, as shown in Fig. 115, also grounds the potential transformer through the line drop compensator, and since the compensator winding has a relatively low resistance and has a current-carrying capacity much greater than that of the potential transformer, this method should be perfectly satisfactory. However, in case the grounding of both transformers is desirable or required, the compensator can be arranged with

a small 1 to 1 insulating current transformer in its base as shown in Fig. 119.

Under certain conditions, approximately the same results can be obtained with a standard line drop compen-

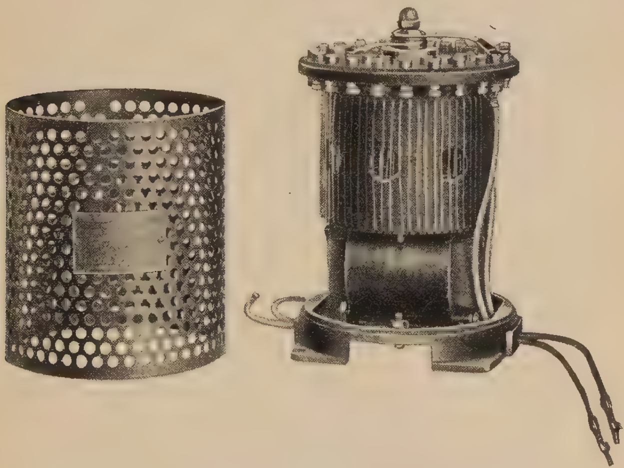


Fig. 119
Type R Form B4 Line Drop Compensator with Current Transformer in the Base

sator and without the use of the insulating current transformer by connecting the auxiliaries as shown in Fig. 120. With this connection, the reactance voltage drop, per step, in series with the current transformer is not uniform as with the connection given in Fig. 115 but varies, the reactance drop varying as the square of the total number of turns of the reactance coil connected in series with the circuit. As a result, the voltage drop per step in the reactance is quite small with only a small number of steps cut in but gradually increases until the voltage drop per step reaches approximately double value. With this connection, the voltage between the last two steps is approxi-

mately 2 volts with full line current flowing, the total range of adjustment, however, remaining as with the standard arrangement. With this connection, the reactance in series with the contact-making voltmeter also is variable.

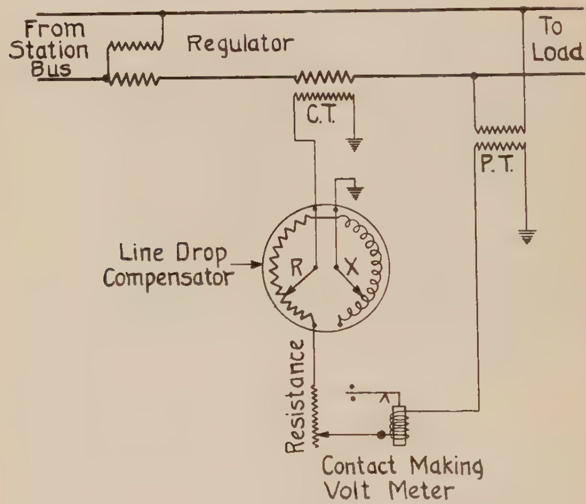


Fig. 120
Connection Diagram of Regulator Auxiliaries with Ground Connections on Both Current and Potential Transformers

Since, however, the reactance is small compared with the value of the ohmic resistance in series with the meter, and since the reactance drop is at right angles to the resistance drop, the error in the adjustment of the meter due to the adjustment of the reactance is small and the resultant voltage regulation is probably sufficiently accurate for all practical purposes. The adjustment of the meter for the no-load condition will therefore give approximately correct line drop compensation if the line drop compensator is properly adjusted.

When it is desired to connect the compensator as shown in Fig. 120 and it is necessary or desirable to obtain the greatest possible accuracy, this error in compensation may be eliminated by the use of a reactance having taps brought out, not in equal steps with reference to the number of turns in the winding but so as to give equal differences in the voltage per step as the dial is moved from tap to tap. As stated, the reactive voltage drop across a reactance varies with the square of the number of turns in series, and by arranging the tap connections in this manner, correct compensation can be obtained with a compensator connected as shown in Fig. 120.

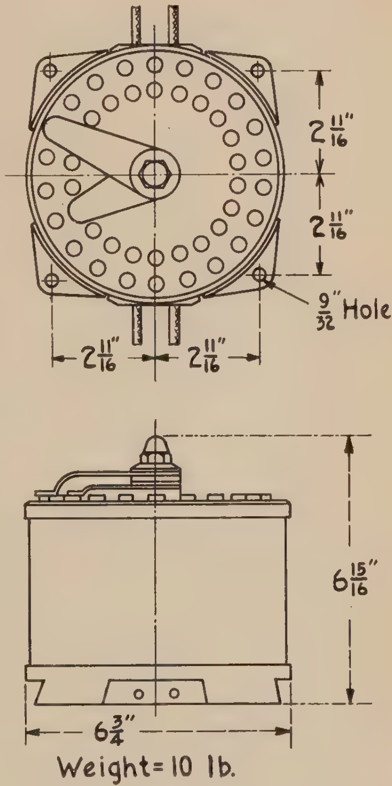


Fig. 121
Dimensions of Line Drop Compensator

Compensators used with single-phase regulators for the control of what may be considered strictly single-phase circuits, that is, single-phase, two-phase and three-phase four-wire circuits, may be so arranged but those used with single-

phase regulators to control a three-phase three-wire system should be provided with the insulating current transformers.

Rating of Compensator

The line drop compensator built by the General Electric Company for use with automatically operated

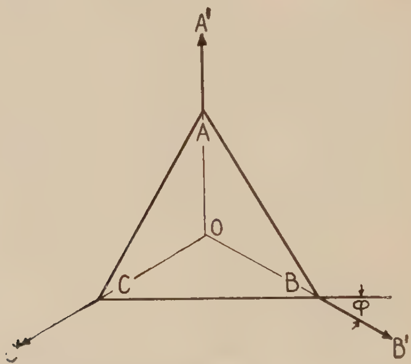


Fig. 122
Phase Displacement in Voltage and Current in a Y-Connected Three-Phase System

feeder voltage regulators is designed to carry the full-load current of standard current transformers (that is 5 amperes) and, with this current flowing, to have a drop of 20 volts across the full amount of resistance and the same voltage drop across the total reactance. The dimensions of the standard compensator are given in Fig. 121. The compensator having the insulating transformer is assembled on the same base as the standard compensator, but it is 4 inches higher.

Compensation for Line Drop in Polyphase Feeders

The diagrams given in Figs. 115 and 120 apply to single-phase circuits whether they are obtained from a

single-phase or a polyphase source of supply. The application of the principles given is, however, general; and, in using line drop compensators for the automatic voltage control of polyphase circuits, the angular relation between line currents and voltages must be considered as well as the phase displacement due to the power-factor.

Three-Phase Feeders

Fig. 122 is a three-phase three-wire diagram in which the voltages between the three phases are represented by *CA*, *AB*, and *BC*; and the currents in the three phases, by CC', AA' and BB'. When the load power-factor is 100 per cent, an angle of 30 degrees results between the voltages and currents as shown in the diagram, for it must be remembered that the voltage between any two phases is the resultant of the two-phase voltages which have an angular displacement of 120 degrees. For instance, *CB* is the resultant of *OC* and *OB*, each of which is in phase with its own phase current CC' and BB'.

In considering the connections of the regulator auxiliaries and assuming the shunt winding of the contact-making voltmeter to be connected across *CB* with a single current transformer in series with BB', then the following results may be obtained. If the phase rotation of the system is clockwise, the current in the series transformer will be in advance of the voltage across the contact-making voltmeter, and if the rotation be counterclockwise, the current will lag behind the voltage by the angle φ which, for a 100 per cent power-factor load, is 30 degrees. That is, the compensation for the line drop is out of phase with the line voltage.

With a power-factor load of 86 per cent, corresponding to a phase displacement of 30 degrees, and with the phase

rotation clockwise, the line current and voltage will be in phase, and correct compensation is obtainable with the connections considered. If the phase rotation were counter-clockwise, the angle would be increased to 60 degrees and practically no compensation would be obtained.

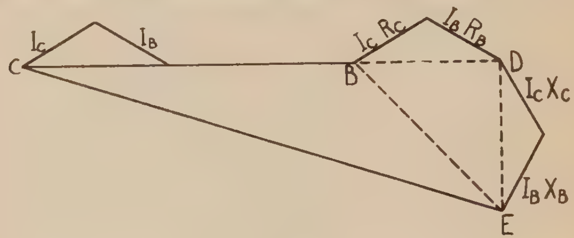


Fig. 123
Compensation for Phase Displacement by the Use of Two Current Transformers

By connecting a current transformer in series with CC' in addition to the one in series with BB', and (if it were feasible) connecting the two transformers in series, we might imagine a resultant current which would be in phase with the voltage CB. Two current transformers in different phases of a polyphase system can not, however, be connected in series because of the phase displacement of the currents in their windings. Each current transformer may, however, be connected in series with a line drop compensator and the line drop compensators may be connected in series so as to obtain the resultant voltage drop due to the current in each series transformer, the voltages across the two compensators being added vectorially.

The same result is obtained if the secondaries of the series transformers are connected to the same compensator (that is, in parallel). The current from each transformer produces a voltage drop in both the resistance and reactance element of the compensator, and the total voltage drop is

the resultant of both the resistance and the reactance drops due to both currents in their proper phase relation. This may be illustrated by Fig. 123 in which CB represents the load voltage and I_C and I_B, the currents of the two phases of the three-phase system considered and indicated in Fig. 122. With a 100 per cent power-factor load, the voltage relations of the line and of the contact-making voltmeter circuit connected to this line will then be as shown.

$I_C R_C$ is the ohmic resistance drop due to current CC' or I_C.

$I_B R_B$ is the ohmic resistance drop due to current BB' or I_B.

$I_C X_C$ is the reactive resistance drop due to the current CC' or I_C.

$I_B X_B$ is the reactive resistance drop due to the current BB' or I_B.

The ohmic resistance drops are respectively in phase with the currents producing them, but the resultant ohmic drop DB is in phase with the load voltage CB.

The reactive resistance drops are respectively at right angles to the currents producing them but their resultant DE is at right angles to the load voltage CB. The total resultant line voltage drop is then BE and the required voltage at the station end of the line, in order to satisfy the conditions given, must be CE in both value and direction.

It should be noted that the results obtained with the preceding arrangement are identical with those obtained with the single current transformer and line drop compensator connected to a single-phase circuit as illustrated in Fig. 116. In a similar manner, it can be shown that correct

compensation is obtained for any power-factor of load as illustrated in Fig. 117.

The resultant voltage drop in both members of the compensator is always proportional in value to the combina-

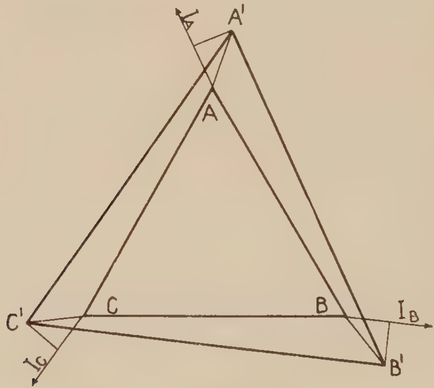


Fig. 124
Vector Diagram of Three-Phase Circuit Showing Voltage Drop Due to Load

tion of currents obtained from the series transformers, whether these currents be balanced or unbalanced. The angular relation of the voltage drop is also determined by the resultant current; hence, correct line drop compensation can always be obtained for any condition of load. By the use of two current transformers, it is immaterial whether the phase rotation be right-handed or left-handed, as either will produce the same voltage drop across the line drop compensator. With an unbalanced or varying power-factor load, the arrangement described should, therefore, always be used on three-phase circuits.

Fig. 124 represents the complete diagram of a three-phase circuit supplying a balanced load of any power-factor. *ABC* is the load voltage; I_A, I_B and I_C the load current; $A'B'C'$ the regulated voltage at the station; and AA', BB'

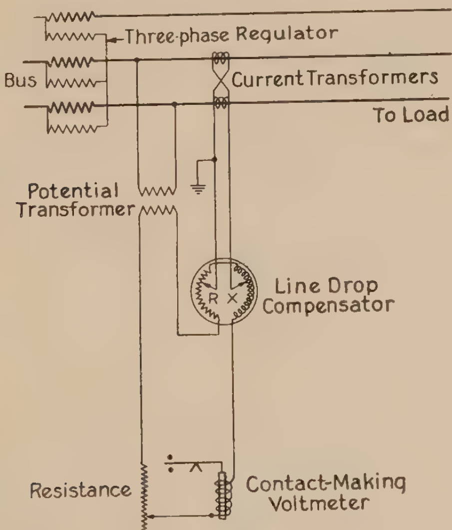


Fig. 125

Connections of One Automatic Three-Phase Regulator on a Three-Phase System

and CC' the voltage drop in the feeder. The total voltage drop per phase and the resultant angular displacement of the line voltages with reference to the line currents are identical for all phases, and the system therefore remains symmetrical. This condition is, however, maintained only under balanced loads, for with varying load requirements on different phases, the voltage compensation per phase will vary in both value and direction depending on the loads. The load voltage *ABC*, as well as the bus voltage, may therefore be symmetrical, but the regulated voltage at the

station (that is, $A'B'C'$) may be unsymmetrical, the voltage across each phase being determined by the character

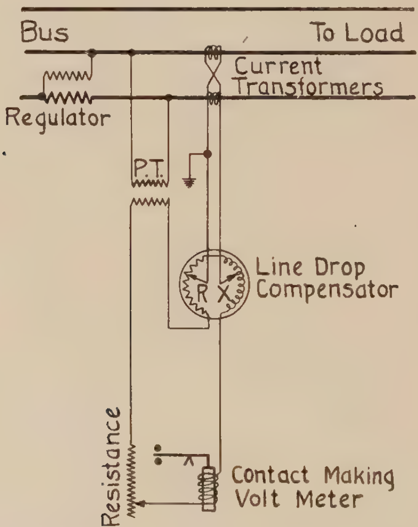


Fig. 126
Connections of One Automatic Single-Phase Regulator on a Three-Phase System

of the load, not only in the individual phase, but on all three phases.

General Diagrams for Three-Phase Circuits

Voltage control on a three-phase system can be obtained by using one three-phase regulator or two or three single-phase regulators, depending on the balance of the load on the three phases and on the voltage regulation requirements.

The general connection diagram for a three-phase regulator control is given in Fig. 125; for one single-phase

regulator on a three-phase circuit, in Fig. 126; two single-phase regulators on a three-phase circuit, in Fig. 127; and

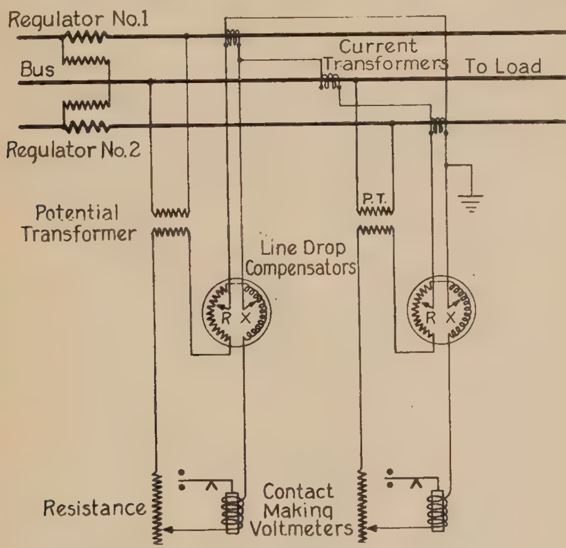


Fig. 127
Connections of Two Automatic Single-Phase Regulators on a Three-Phase System

three single-phase regulators on a three-phase circuit, in Fig. 128.

Fig. 126, the general connection diagram of a single-phase regulator operated on a three-phase circuit, shows the use of two current transformers with a single line drop compensator. The same arrangement may be used when two or three single-phase regulators are required for the control of the three-phase system. That is, each single-phase regulator control may consist in part of two current transformers and a line drop compensator, each line drop compensator being connected to two current transformers

in different places as illustrated in Fig. 126. This arrangement would result in the use of four current transformers for the control of two regulators and six current transformers for the control of three regulators. However, the

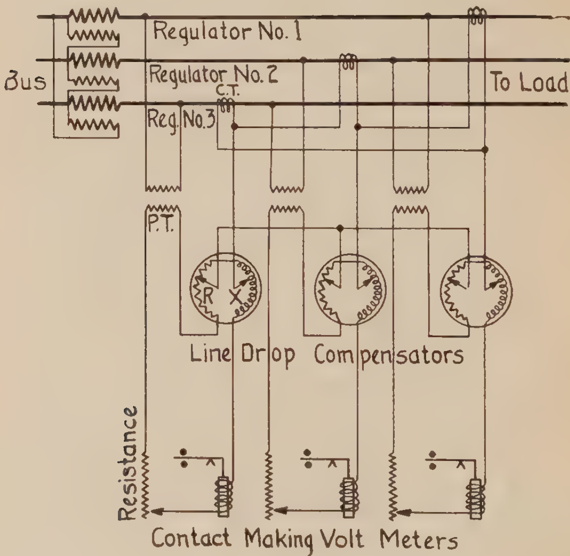


Fig. 128
Connections of Three Automatic Single-Phase Regulators on a Three-Phase System

same results are obtained by the use of a single current transformer for each phase and interconnecting these transformers as shown in Figs. 127 and 128.

With two parallel-connected current transformers in series with each line drop compensator, as indicated in Figs. 125 to 128 inclusive, the current in the secondary of each transformer will be proportional to the current in the line in which the transformer is connected in the ratio of

the turns of the transformers. These currents will, however, be out of phase by 120 degrees and the combined current on a balanced system will therefore be 1.73 times the current in each phase. In other words, with the full-load

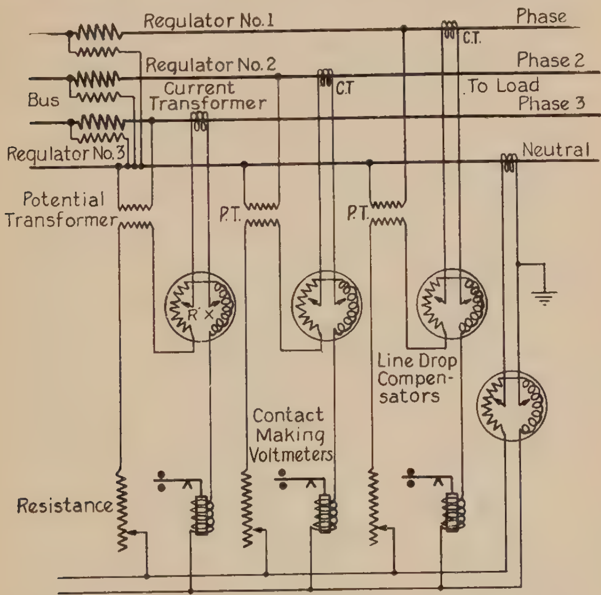


Fig. 129
Connections of Three Automatic Single-Phase Regulators on a Three-Phase Four-Wire System

current of 5 amperes on each transformer, the current in the compensator will be 8.65 amperes.

In order to use a standard compensator, it is therefore necessary to select current transformers of a higher ratio so that, with full load on the primary, the secondary current will be 5 divided by 1.73 or practically 2.9 amperes. Transformers of normal ratio could be used, but they would require a line drop compensator having a larger capacity

and a greater loss. For this reason, and because all of the apparatus required is standard stock material, the arrangement suggested is preferable.

In a four-wire three-phase unbalanced system, the voltage drop in the neutral wire may be detrimental and may require voltage compensation. Correct compensation can be obtained as shown in Fig. 129. It is obvious that, for the best results, single-phase regulators should be used in this case.

Two-Phase Feeders

Two-phase feeders may be operated as four-wire or three-wire lines. The four-wire quarter-phase system may be considered as consisting of two single-phase feeders displaced by 90 degrees but having no electrical connection between the phases. The line drop compensator connection is therefore identical to that used for a single-phase feeder, that is, only a single current transformer is required for each regulator. The connections for one-phase are shown in Fig. 115. As in the three-phase system, however, an unbalancing of the load changes the individual line compensation requirements and thereby changes the angular relation between the phases.

In the two-phase three-wire system, the two phases have a common return. The voltage drop in each phase is that due to the drop in the phase wire for each phase, plus the voltage drop in the common return. This latter voltage drop is, however, due to the currents in both phases. The current in each phase therefore produces a voltage drop, not only in its own phase, but also in the other phase so that interconnected transformers are required as in the three-phase system.

Fig. 130 illustrates the voltage relations in both phases with a balanced load, and Fig. 131 shows them after the load voltages are again equalized. In the diagram (Fig. 130), the generator voltage is represented by *ABC*, the phase voltages being equal and at an angle of 90 degrees.

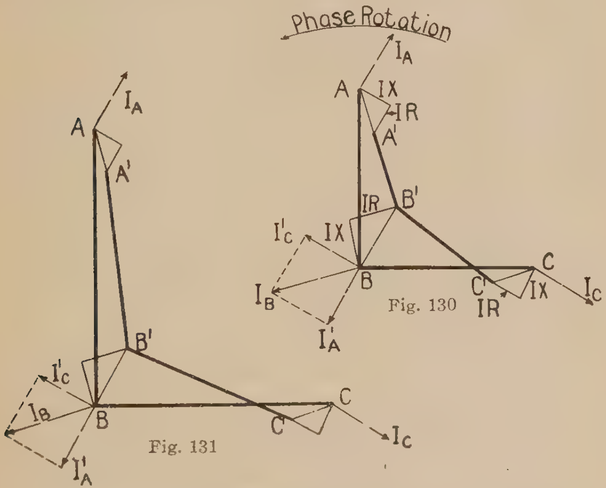


Fig. 130

Fig. 131

Figs. 130 and 131
Vector Diagrams of Quarter-Phase System Showing Line Voltage Drop and Corrected Voltage

The currents in the individual phases, represented by I_A and I_C are also equal and at right angles. The current in the common return is therefore I_B and is displaced 45 degrees from both I_A and I_C and has a value of $\sqrt{2}$ times the phase current. *IR* and *IX* represent the ohmic and reactive resistance drops.

Assuming the common return feeder to be of the same section as the phase wires, the values and directions of the voltage relations, for the particular power-factor indicated

by the angle between the line current and voltage, are then as given. It will be observed that the voltages at the load $A'B'C'$ are unequal and are no longer at right angles. These voltages are again equalized in value, as shown in Fig. 131 by means of individual single-phase regulators but they are still displaced from their normal positions. This relation is one of the characteristics of this system of distribution.

An unbalancing of the load on the two phases or a difference in the power-factor of the loads may further unbalance the system so that a still greater divergence in the voltages of the phases may occur than is indicated in the diagrams given. Correct voltage compensation can be obtained by the individual voltage control of each phase by connecting the auxiliaries as shown in Fig. 132; but the proper phase relation between the two phases, that is, a displacement of 90 degrees, can not be so obtained.

In the arrangement shown, it should be noted that each phase has its own current transformer and line drop compensator, and that the common return circuit is through a third compensator. The two currents in the third compensator are each in phase with their respective line currents and proportional to them as in the three-phase connection, and each produces an ohmic and reactive voltage drop which is added directly to the voltage drop obtained from the line drop compensators in the corresponding outside phase. Each contact-making voltmeter is in series with its own compensator and the third compensator so that, under all conditions of load and power-factor, correct voltage compensation is obtained in each phase.

In the diagrams, Figs. 130 and 131, I'_A and I'_C (the currents in the third compensator) are respectively equal to, and opposite in phase from I_A and I_C. The effective

resultant current is therefore I_B and the resultant voltage drops, ohmic and reactive, are respectively as shown in phase with and at right angles to this resultant current. The total resultant voltage drop in the common line wire is

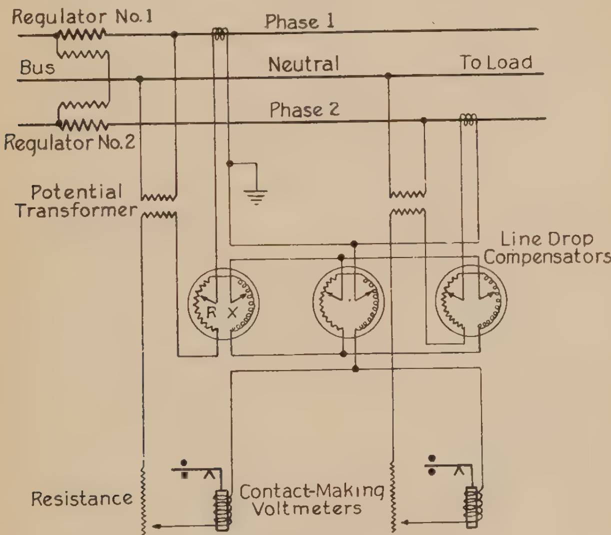


Fig. 132
Connections of Two Automatic Single-Phase Regulators on a Two-Phase Three-Wire System

BB' which is combined with the voltage drop in each of the phase lines as shown. From the diagrams, it will be noted that the current in the common compensator is always the resultant of the two line currents and therefore has a maximum value of 1.42 times the line current. Thus, if 5 amperes in the secondary of the current transformer represent full load on the line, a special line drop compensator having a current capacity of 7.1 amperes will be required for the common return.

Adjustment of the Line Drop Compensator

As has previously been stated, constant voltage with varying load conditions can be maintained at only a single point on the feeder. The maintenance of a constant voltage

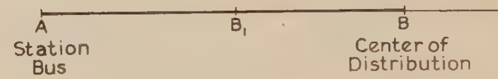


Fig. 133
Distribution of Load on a Feeder

at a predetermined point depends, however, on the distribution of the load on the feeder regulated as may be illustrated by Fig. 133. Assuming the distributing station at A and the feeder as shown, with the line drop compensator adjusted to hold a constant voltage at B, then, with the total load at B, correct compensation will be obtained; but with a varying load at B_1, the voltage at B will vary depending on the variation of the load at B_1. The line drop compensator is adjusted for the total resistance and the reactance of the line from A to B, and the current taken at B_1 produces a voltage drop in the line drop compensator at the same rate as the current taken at B.

The current taken at B_1 does not, however, produce the same voltage drop in the feeder as the current taken at B, but produces a drop which is proportional to the relative distance of B_1 and B from A. If, for example, B_1 is one-half as far from A as B is, and if 100 per cent current flowing from A to B produces a 10 per cent voltage drop, then, with the same current flowing to B_1, the voltage drop is only 5 per cent. If, however, the compensator is adjusted to hold constant voltage at B and the full load is taken at B_1, the voltage at B, and B_1 as well, will be 10 per cent

greater than the bus voltage; that is, 5 per cent higher than desired.

The compensation for the line drop to any predetermined point on a feeder is, therefore, modified and

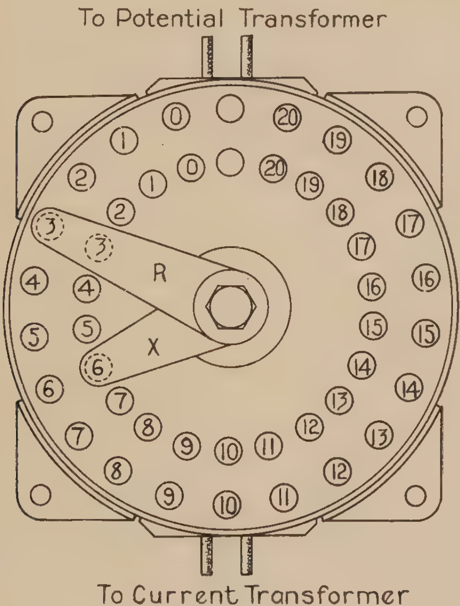


Fig. 134
Diagram of Line Drop Compensator Dial

affected by any load taken from the regulated feeder between the distributing station and the point on the line where constant voltage is desired. This error in compensation depends upon the relation of the intermediate load to the load at and beyond the point considered, and to its relative distance from the station. In considering the adjustment of the line drop compensator, it will therefore

be assumed that the load is concentrated at a single point on the line and that a constant voltage is desired at this center of distribution.

There is only one combination or adjustment of the two dials of the line drop compensator which will give a constant voltage at the center of distribution for all conditions of load. Fig. 134 shows the dials of the line drop compensator manufactured by the General Electric Company. The arm *R* controls the resistance element, and the arm *X*, the reactance element. The number of the plugs or steps of these elements indicates the voltage drop included in the contact-making voltmeter circuit with full-load current (that is, 5 amperes) flowing in the secondary of the current transformer. The standard compensator has 4 ohms resistance and 4 ohms reactance, each divided into 20 equal steps, so that, under full load (or with 5 amperes flowing), the voltage drop in each member is 20 volts or practically 1 per cent per step when used with a 110-volt potential transformer.

As shown in Fig. 115, with both arms on the zero plug, no compensation is obtained. To obtain correct compensation for all conditions of load, each arm is moved to the plug corresponding to the per cent resistance and reactance drop of the line, with full-load current flowing.

The resistance and reactance of the line can be calculated if the following values are known:

Length of line.
Section of conductor.
Spacing of conductor.
Line current, and
Frequency.

The following table gives the ohmic resistance and inductive reactance, in ohms, of single-phase 60-cycle

circuits one mile (5280 ft.) long, i.e., 10,560 feet of conductor of the standard sizes of copper wire most commonly used, and for several spacings of the conductors. Values for other conditions can be obtained from standard Handbooks.

B.&S. GAUGE	OHMIC RESISTANCE	INDUCTIVE REACTANCE (IN OHMS)				
		6-In. Interaxial Distance	9-In. Interaxial Distance	12-In. Interaxial Distance	18-In. Interaxial Distance	24-In. Interaxial Distance
0000	0.5080	0.8500	0.9504	1.0206	1.1190	1.1885
000	0.6388	0.8802	0.9789	1.0486	1.1400	1.2170
00	0.8064	0.9087	1.0069	1.0766	1.1730	1.2450
0	0.0170	0.9367	1.0349	1.1046	1.2000	1.2730
1	1.2880	0.9646	1.0634	1.1331	1.2300	1.3010
2	1.6161	0.9932	1.0914	1.1611	1.2598	1.3295

As an illustration of the adjustment of the compensator, the following example is given:

EXAMPLE:

Length of line . . . . $1\frac{1}{2}$ miles
Section of conductor . . . . No. 00 B.&S.
Spacing of conductors . . . . 18 inches
Line current . . . . 100 amperes
Frequency . . . . 60 cycles
Line voltage . . . . 2300 volts
Potential transformer ratio 2300/115
Current transformer ratio 150/5
Ohmic resistance (from table) . . . . . . 1.21 ohms
Inductive reactance (from table) . . . . 1.75 ohms
Ohmic line drop . . . . 121 volts = 5.26 per cent
Reactive line drop . . . . 175 volts = 7.63 per cent

Reduced to the low-voltage side of the potential transformer the line drop is:

Ohmic drop . . . . 5.26 per cent = 6.05 volts
Reactive drop . . . . 7.63 per cent = 8.75 volts

Due to the ratio of the current transformer used, the current on the low-voltage side of this transformer is 3.33 amperes with full-line current flowing so that, if the compensator gives 1 volt drop per step at 5 amperes, each step is now 0.6 volts.

The resistance lever R of the compensator is therefore to be placed on the tenth point, corresponding to 6.0 volts, while the reactance lever X is to be placed on the fifteenth point, corresponding 9.0 volts.

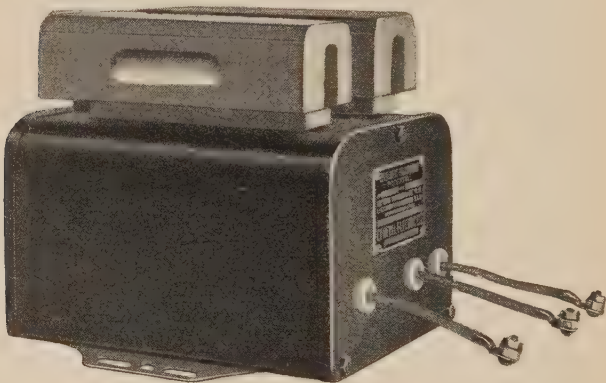


Fig. 135
Type E-12 Instrument Potential Transformer

If the line constants are not obtainable as indicated, the only method of adjusting the compensator is by trial.

If the power-factor of the load is high, the line drop is due almost entirely to the ohmic resistance of the line. With the reactance lever on zero, the resistance lever of the compensator should be adjusted so as to obtain correct voltage at the center of distribution. As the power-factor of the load decreases with the reduction in the load, the compensation becomes incorrect. The resistance lever should not be changed, but the reactance lever should now be adjusted so as again to obtain correct voltage. This adjustment of the compensator should be the proper one for all load conditions.

If the power-factor of the load is unknown or varies for the same amount of power transmitted, the following method is the only feasible one.

An indicating voltmeter should be connected to the line at the center of distribution and telephonic communi-

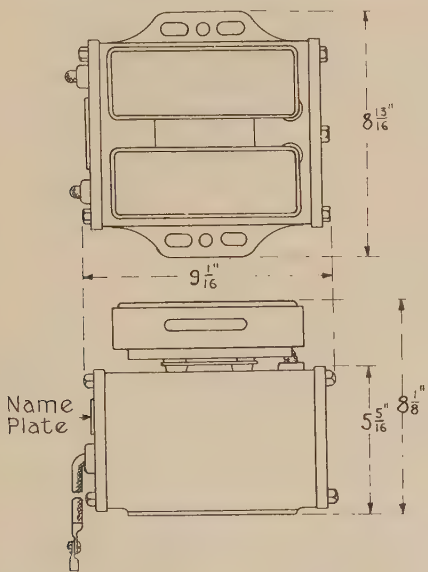


Fig. 136
Dimensions of Type E-12 Potential Transformer

cation should be established with the operator at the station. Unless the resistance drop in the line can be ascertained or approximated so that the resistance dial can be adjusted for the line current flowing, the resistance lever should be set at plug 1, and with this setting of the resistance lever, the reactance lever should be moved successively from plug 0 to plug 20. If correct compensation

can be thus obtained, the positions of both the resistance and reactance levers should be recorded. The resistance lever should then be set on plug 2 and the entire series of

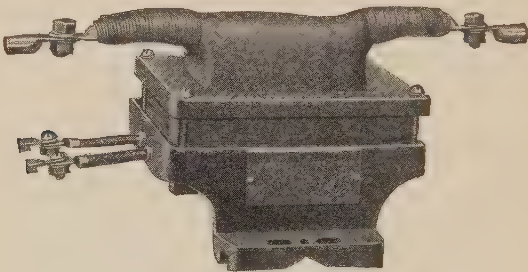


Fig. 137
Type W-2 Current Transformer

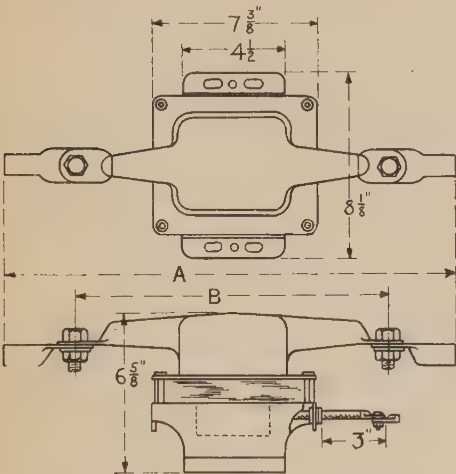
adjustments of the reactance dial repeated, and so on for every resistance adjustment.

All of the combinations of resistance and reactance adjustments giving correct compensation should be noted and the entire investigation should be repeated a number of times with loads of different values and power-factors. There will probably be a number of different combinations which will satisfy any given load, but, as previously stated, only one combination will satisfy all conditions of load and power-factor. The correct combination is obtained by comparing the various combinations obtained for each load condition, and the combination common to all is the one for which the compensator should be adjusted.

Potential and Current Transformers

The potential and current transformers used with the line drop compensator are of the standard station design. The potential transformer usually used on a 2300-volt circuit is shown in Fig. 135, and the overall

dimensions are given in Fig. 136. The current transformer for the same voltage circuit is shown in Fig. 137, and the overall dimensions are given in Fig. 138.



AMPERES	DIMENSIONS IN INCHES	
	A	B
200	17	12¾
300	19½	13¾
5 to 100	15½	12¼
125 to 150	16⅞	12¾

Fig. 138
Dimensions of Type W-2 Current Transformer

It is sometimes impossible to obtain sufficient line drop compensation with a standard line drop compensator and the current transformer used. The difficulty is usually due to the use of a current transformer of too high a ratio, the current in the secondary of such a transformer being too small to produce the compensating voltage drop required in the compensator. The current transformer should have such a ratio that, with the maximum load on the feeder, the secondary current of the transformer has a value of 5 amperes.

SECTION XVIII

TIME OF OPERATION OF THE REGULATOR

An instantaneous compensation for line voltage changes and fluctuations would be ideal, but this is physically impossible with the induction regulator and it is not usually essential. The regulator generally used for feeder voltage regulation has a kv-a. capacity capable of producing in the feeder regulated a total voltage change of 20 per cent (that is, 10 per cent boost and 10 per cent lower), and feeders are normally designed so that the voltage drop from no load to full load does not exceed this amount.

Feeders on which good voltage regulation is required are usually limited to those supplying lighting loads or mixed lighting and power loads. If the power load consists of motors, they are usually limited in size so that their starting currents do not appreciably affect the line voltage unless such motor loads are fairly constant and the motor is not subject to frequent starting and stopping. Except under unusual conditions, the load on a lighting feeder therefore varies more or less gradually, and as, moreover, a small voltage variation is allowable as well as unavoidable, the speed of the regulator, for all practical purposes, need not be greater than that required to compensate for normal load changes which cause corresponding voltage changes greater than allowable for satisfactory illumination.

A voltage fluctuation of 2 per cent is usually permissible on a lighting feeder as this variation does not produce an appreciable visual change in the candle-power of the incandescent lamp (which is usually the criterion of the voltage regulation requirements). On the assumption that the total line drop at full load is 20 per cent, to produce a voltage variation of 2 per cent requires a load change of 10 per cent, and it would seem that the instantaneous load

changes on lighting feeders operating under normal conditions should not exceed this amount. However, because of the increasing tendency to supply power loads from lighting feeders, and because of the use of larger motors, modern regulators are designed so as to compensate for voltage changes in as short a time as practicable and as operating conditions seem to demand. The limiting features making instantaneous compensation impossible and which determine the time of operation are:

The time required by the contact-making voltmeter to make contact,

The time required by the relay switch to connect the operating motor of the regulator to its source of power.

The time necessary for the operating motor to start and to attain speed, and

The time required for the regulator armature to be rotated through a sufficient angle to compensate for the change in the line voltage.

With the contact-making voltmeter in the normal position and subjected to an instantaneous voltage change, the time required to make contact is about 0.1 second, and the time required by the relay switch is approximately 0.14 second. The motor armature having, however, a greater mass and operating at a high speed requires about 0.16 second to start and an additional 0.24 second to attain full speed even though regulator operating motors are always designed so as to have a maximum torque at zero speed. The total time required for the regulator to start to adjust the line voltage from the time the change in voltage occurs is therefore about 0.4 second, and the time necessary to adjust the voltage depends upon the per cent range for which the regulator is designed, upon the position

of the regulator with reference to its range in voltage control, and upon its mechanical size and kv-a. capacity.

A regulator of any given kv-a. capacity and wound for a given frequency and line voltage is assembled in a given

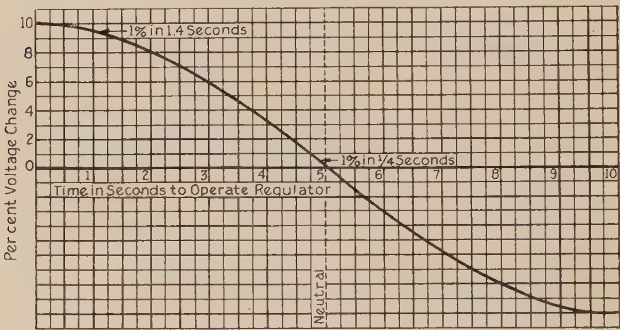


Fig. 139
Voltage Change Produced by the Rotation of the Induction Regulator

set of parts and operated by the same design of mechanism regardless of whether the voltage range be 10, 15 or 20 per cent. Thus, the time required to produce 1 per cent change in voltage is twice as great for a 10 per cent regulator as for a 20 per cent regulator of the same size.

The voltage range produced by the induction regulator follows a sine curve so that, as illustrated in Fig. 139, a much longer time is required to produce a 1 per cent change with the regulator near either limit of its range than at the neutral position.

Since the maximum torque of a polyphase regulator is equal to that of an induction motor of the same output and speed, it is necessary to adjust the regulator with an operating motor having the same torque in the ratio of the gearing divided by the efficiency of the operating mech-

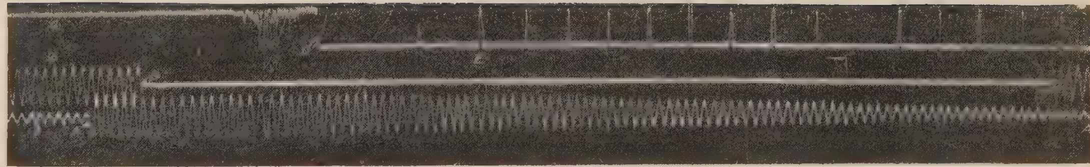
anism. With a given ratio of gearing, the torque of the motor would therefore be proportional to the kv-a. capacity of the regulator.

The inertia of the motor, however, increases at a higher rate than its kv-a. output so that, in order to maintain the same speed of operation for all regulators, the operating mechanism would have to be increased in size and strength at a much greater rate than required by the kv-a. capacity of the regulator itself, and solely in order to compensate for the increased inertia of the motor. Lack of space on the cover of the regulator, and the cost are, however, usually prohibitive, for this arrangement would require much larger operating motors than are used at the present time. The difficulties of electrical and mechanical control by means of the relay switch and the brake would also be increased to a considerable extent in the larger sizes of regulators. For the reasons given, the larger sizes of regulators are therefore normally designed so as to require a greater length of time for their operation than the smaller sizes. This, however, seems a logical arrangement when it is considered that the larger regulators are used to a greater extent for power circuits and the smaller sizes for lighting circuits. The former do not require so close or so rapid a voltage regulation as the latter.

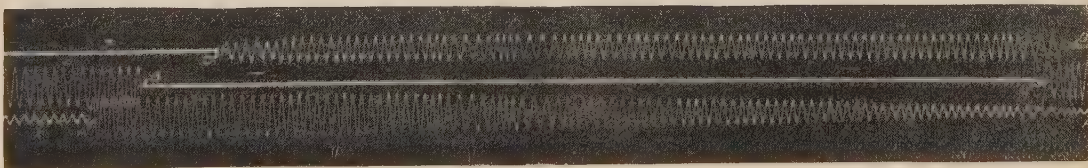
Oscillograms

Fig. 140 shows one set of a number of oscillogram tests taken to determine the time of operation of the various regulator control units. Fig. 141 shows their interpretation.

The two sets of curves given in Fig. 140 were taken simultaneously on two oscillographs as four curves were required and only three could be taken with a single instrument. Curve No. 1 on each oscillogram represents



Oscillogram No. 1



Oscillogram No. 2

Fig. 140

Oscillograms Showing Time of Operation of Induction Regulator Auxiliary Apparatus

1. Line Voltage *A*—Load Voltage Changes
   A′—Voltage Corrected
2. Voltage on Contact-Making Voltmeter Contacts
   B—Contacts Closed
   b—Contacts Open
3. Voltage on Motor Terminals
   C—Relay Switch Closes
   G—Switch Opens
4. *D*—Operating Motor Starts
   E—Reached Full Speed

the line voltage variation, and as actually taken, is the difference between the voltage at the generator and at the load. At point A on this curve, a load was thrown on the circuit thereby causing a difference in the voltage between the generator and the load, that is, a difference due to line drop and as indicated by the increased width in the curve at this point. Due to the voltage adjustment by the regulator, the amplitude of the voltage difference per cycle decreases until the voltage is again normal. The length of time required is represented by the length of the curves given and is determined definitely in seconds by counting the number of alternations or cycles of the circuit between the points of time at which the various regulator auxiliaries operated. The tests given were taken on a 60-cycle circuit.

Curve No. 2 represents the voltage across the contact-making voltmeter contacts. At point B, the contacts close, point B being 5.5 cycles later than point A on curve No. 1. As the frequency of the circuit is 60 cycles, the time required for the contact-making voltmeter to close the relay switch circuit after the voltage change has taken place is 0.091 second.

Curve No. 3 represents the voltage on the operating motor and the closing of the relay switch which occurs at point C. Point C is 8.5 cycles later than point B on curve No. 2 and represents 0.138 second.

Curve No. 4 was taken by attaching a wiping contact to the operating motor's shaft and recording the engagements of the rotating contact with a stationary one. The interruptions on this curve therefore represent revolutions of the operating motor. Point D indicates the starting of the motor, and the length of the curve sections between the interruptions, referred to the frequency of the circuit as shown in curve No. 1, gives the acceleration. Point D

is 0.163 second behind the closing of the relay switch, and at point E (0.292 second later), the motor is running at full speed.

The opening of the contact-making voltmeter is shown at F, and the opening of the relay switch at G. The motor,

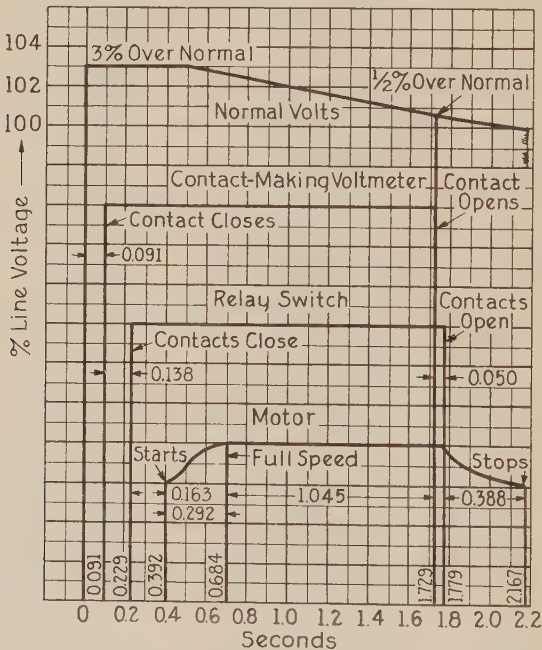


Fig. 141
Curve Showing Time of Operation of Induction Regulators and Auxiliary Apparatus

however, overruns to some extent, as intended, until curve No. 1 is again practically a straight line representing normal voltage.

The curves given in Fig. 140 and interpreted in Fig. 141 are approximately correct for the auxiliaries used with all automatically operated regulators. The difference in time

of operation of different designs and sizes of regulators is due to the difference in the ratio of their gearing. The relative importance with regard to time of operation of the

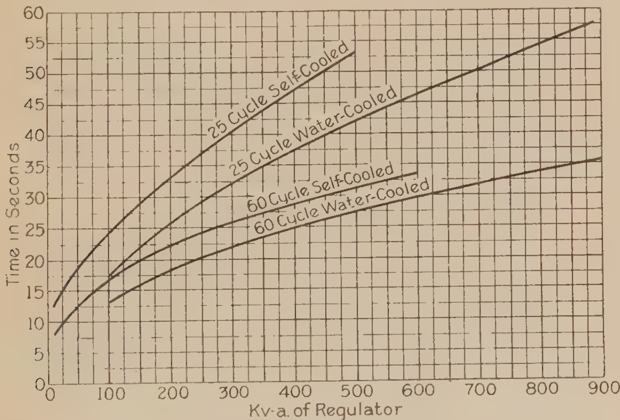


Fig. 142

Approximate Time of Operation of 2300-Volt Induction Regulator from Maximum Boost to Maximum Lower

various units composing an automatic induction voltage regulator are therefore as follows:

1. The regulator itself. (The time of operation depends on the kv-a. capacity as illustrated in Fig. 142 and on the position of the regulator with reference to the boost and lower curve as illustrated in Fig. 139. The curve shown in Fig. 139 shows that the time required by the regulator to produce a 1 per cent voltage change varies from 0.25 to 1.4 seconds for a 10-second regulator, and Fig. 142 indicates that it takes several times as long to produce the same voltage change by means of larger regulators.)

2. The operating motor. (The time required to start the smallest size of regulator motor from rest is practically 0.3 second.)

3. The relay switch. (The time required to operate is 0.14 second.)

4. The contact-making voltmeter. (Its time is 0.1 second.)

The importance of the time of operation of any or all of the units composing an automatic voltage regulator depends on the normal amplitude and frequency of the feeder voltage changes requiring correction and on the requirements of the service.

In view of the limitations imposed by the torque of the regulator and by the size and inertia of an operating motor capable of overcoming the regulator torque, no radical reduction in the total time of operation of this design of regulator can be expected except at a considerable increase in both initial and operating costs, and as indicated, such increase in costs does not seem to be justified under present operating conditions and requirements.

PART III

THE APPLICATION AND SELECTION OF FEEDER REGULATORS

SECTION XIX

THE POLE TYPE OF REGULATOR

Application

In modern generating and distributing stations, constant voltage is usually maintained at the bus, and an automatically operated induction voltage regulator is installed in each feeder to compensate for its voltage drop due to varying loads so as to maintain a constant potential at its center of distribution. Such regulators are generally installed in the station from which the feeders emanate, but conditions occur which require the installation of the regulator at or near the center of distribution. To satisfy such conditions, the General Electric Company has designed and developed a self-contained automatically operated regulator designated as the *PIRS* or pole-type induction regulator, single-phase.

A comparatively large number of regulators of this design have been in service for several years, some operating under the most severe conditions, and they have fully demonstrated their reliability even with practically no attention. This design of regulator is built for the control of single-phase circuits only, and is used advantageously for regulating the voltage of a feeder taken from a transmission or power system and supplying a small village or community.

The voltage across the transmission line varies along the line and according to the main load. The only method of insuring a constant voltage across the branch feeder is therefore the installation of an automatically operated regulator connected in that feeder and controlling the voltage of its load.

The same conditions prevail on a long feeder from which power is taken at a number of points along its length. In addition to the station voltage regulator controlling the

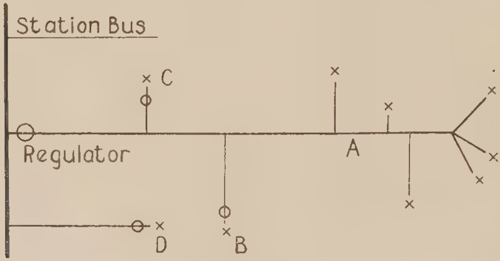


Fig. 143
Feeder Regulators Recommended on a General Distributing Feeder

voltage of the feeder so as to satisfy the main requirements, it is sometimes advantageous as well as economical to control independently the voltage of some of the subsidiary feeders at their junction with the main feeder or at their center of distribution as indicated in Fig. 143. As illustrated in this diagram, the main regulator is in the generating or distributing station and maintains a constant voltage at the principal point of distribution as at *A*. Due, however, to variations in voltage between the station bus and at the loads *B* and *C*, small auxiliary regulators of the outdoor type are required at these points to insure a satisfactory voltage regulation.

The pole type regulator is also well adapted for controlling the lighting circuits of an isolated factory obtaining power from a single line as at *D*, for it is usually much more important to insure good voltage regulation for

illumination than to maintain this same degree of voltage regulation on the power circuits.

Design of Pole Type Regulator

The PIRS regulator is of the induction type and is shown in Fig. 144. The operating mechanism is of a

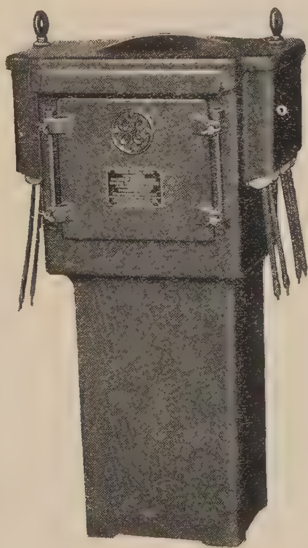


Fig. 144
Pole-Type Single-Phase Automatic Feeder Voltage Regulator

different design from that heretofore described, in that it is entirely mechanical and is devoid of current-making or current-breaking contacts.

The regulator with its operating mechanism is contained in a substantial weatherproof cast iron tank arranged for pole mounting and the entire design is simple and

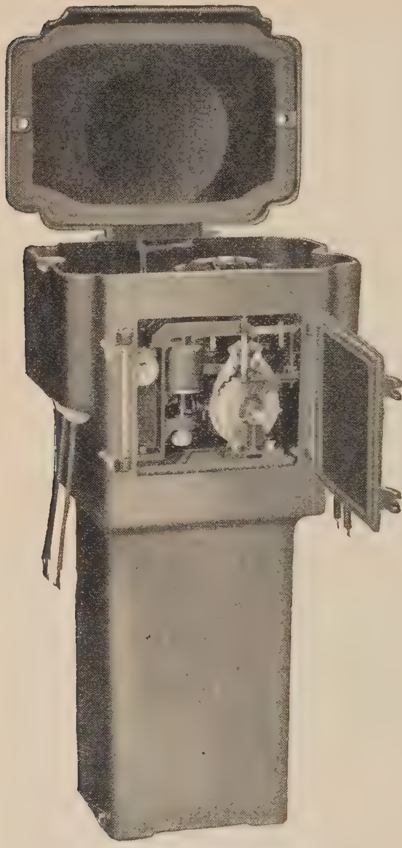


Fig. 145
Pole Type Single-Phase Automatic Feeder Voltage Regulator with Door and Cover Open to Show Mechanism

substantial in construction, as shown in Figs. 144 to 152 inclusive.

Figs. 144 and 145 show the regulator complete. In the latter illustration, the cover and door are shown open for inspection. Both the cover and door are provided with gaskets, and the leads are sealed into and brought out through sealed-in porcelain bushings, making the tank weatherproof. Fig. 146 shows the regulator complete and removed from the tank. Fig. 147 shows a sectional view of the regulator without the mechanism.

The riveted frame type of construction is used, and the frames or flanges for both stator and rotor are exceptionally rigid and heavy. The flanges not only securely clamp and hold the laminations in place, but also support the bearings of the stator and the shaft of the

rotor, and thus insure a uniform air gap. The laminations and windings are of the well-known single-phase design; the stationary punchings contain the secondary or series coil and the rotor contains the primary or shunt winding as well as the short-circuited winding.

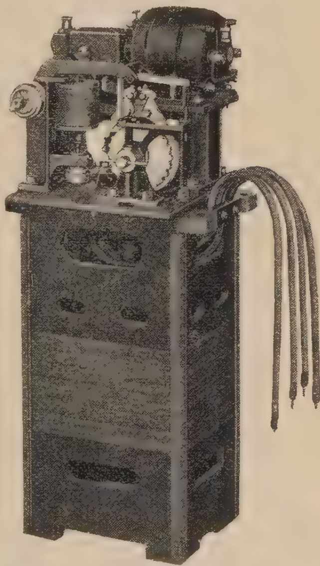


Fig. 146
Pole Type Single-Phase Automatic Feeder Voltage Regulator Removed from Tank

The series coil is form wound. The shunt coil is wound directly on the rotor, and the primary flanges (which are of bronze) and the holding rivets (which are of hard copper and are placed at right angles to the shunt windings) serve as the short-circuited winding. Flexible leads are brought out through the top flange of the rotor and, for flexibility, are wound around the shaft as in the standard station type of regulator. Oil stops are also provided as in the standard station design.

The operating mechanism is a redesign and modification of the Thury regulator and is shown in Figs. 148 and 149. It consists of the voltage relay, the operating motor, the interconnecting mechanism, and the limit device.

The voltage relay consists of a coil, a core, and a dashpot. The relay is connected in series with an adjustable non-inductive resistance and must be excited from the regulated side of the feeder, preferably at 110 volts. The

solenoid and core of this relay are similar to those of the contact-making voltmeter used to control the station type of regulator, but in the present case, the relay is arranged

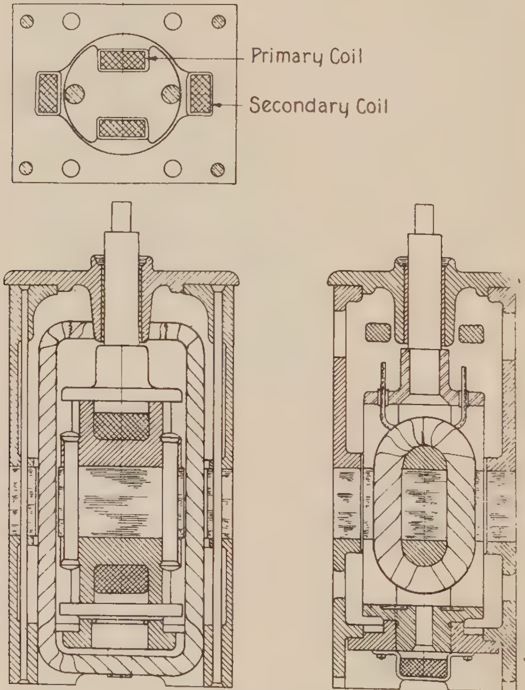


Fig. 147
Sectional View of Pole Type Single-Phase Regulator

with a dashpot instead of with holding coils. Holding coils are not required as there are no electrical contacts, for the operation of this relay is entirely mechanical The core of

the relay is suspended from a balance arm M as shown in Fig. 148 and is counterweighted by an adjustable spring and by the magnetic pull of the solenoid, which pull is adjustable by means of the variable series resistance. The

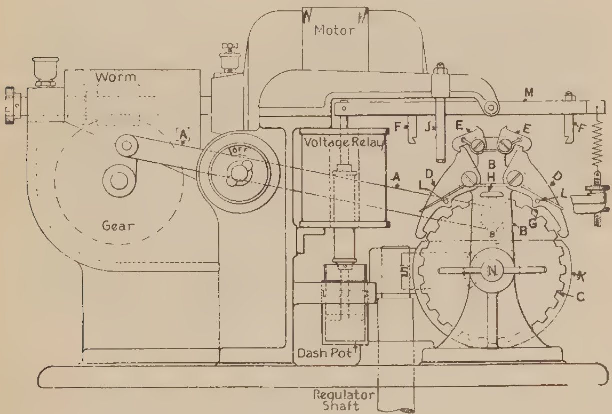


Fig. 148
Mechanism for Pole Type Single-Phase Regulator

balance arm is provided with two trip pins FF which cause the regulator to be adjusted by means of the operating motor and mechanism. If the regulated voltage is correct, these trip pins clear the mechanism, and if incorrect, one or the other causes the regulator to be rotated until the voltage is properly adjusted.

The operating motor shown in Fig. 150 is substantially designed and is provided with high-grade ball bearings. It is wound single-phase and is arranged with an automatic centrifugal switch to cut out the starting winding as soon as the motor has attained speed. The main and starting

windings are on the rotor, and power is supplied by means of two collector rings and simple accessible brushes. The motor runs continuously at 1800 r.p.m.; its power consumption is approximately 30 watts. As designed and

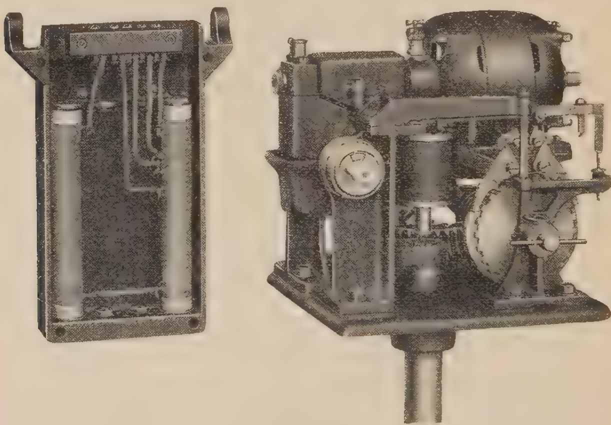


Fig. 149
Operating Mechanism and Resistance for Pole Type Single-Phase Automatic Regulator

operated, no troubles or difficulties are experienced with this motor, but its mounting is so arranged that, as shown in Fig. 151, it can readily be removed without taking the regulator out of the tank or disturbing any other mechanism. The motor and relay are generally supplied with power from the same source, and for convenience in inspection, a snap switch is provided in the motor and relay circuit. For safety, the motor circuit is also fused, the fuse blocks being mounted inside of the regulator tank.

The interconnecting mechanism (Fig. 148) consists of a motor worm gear and a crank on the motor worm gear

shaft; a connecting or driving rod *AA* connecting the motor gearing to the regulator-driving mechanism; a rocker arm *B* loosely mounted on the regulator worm shaft *N* and on which rocker arm there is mounted a pair of ratchets *DD*

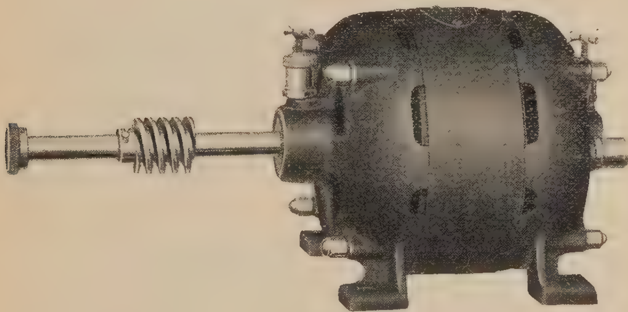


Fig. 150
Operating Motor for Pole Type Single-Phase Regulator

and their triggers *EE* which arm with its ratchets and triggers is oscillated by the rotation of the motor and by means of the connecting rod *AA*; a notched wheel *C* which also is mounted on the regulator worm shaft *N* but keyed to it so that any movement of *C* and *N* in either direction is transmitted to the operating shaft of the regulator; and the regulator worm and segment. Under normal voltage conditions, the triggers *EE* are in engagement with their ratchets *DD* the former of which pass under and clear the trip pins *FF* on the balance arm, and the latter of which clear the notched wheel *C*.

The limit device consists of the cam *K* loosely mounted on the regulator worm shaft *N* and arranged to engage with the regulator worm gear segment *S* at its limits of travel and with the pawls *DD* by means of the pins *LL*. Fig. 152 shows the construction of this device, and it will be noted

that it is very similar in construction and operation to the limit switch used with the station type of regulator. The engagement between the regulator segment and the cam

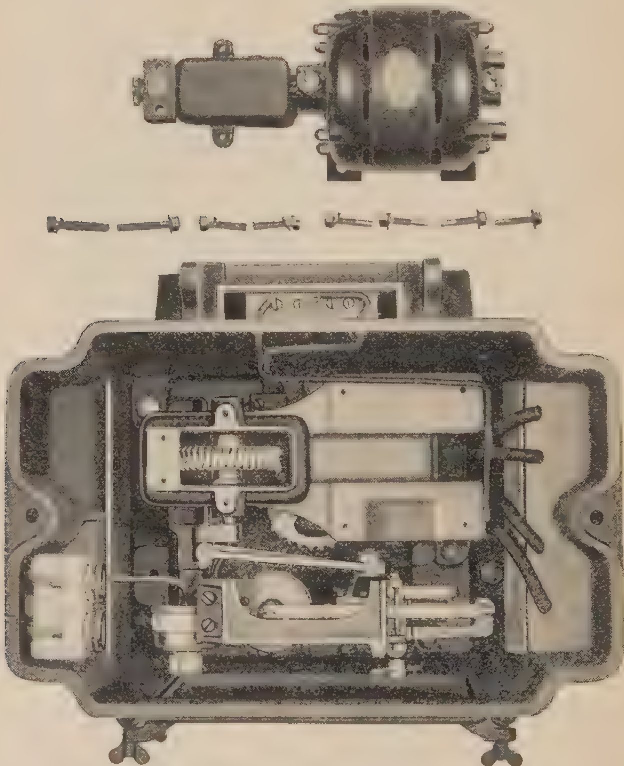


Fig. 151
Top View of Operating Motor and Mechanism of a Pole Type Single-Phase Regulator

K is obtained by an elbow or bell crank one arm of which engages with the segment and the other with the cam.

The elbow is mounted on a vertical stud as shown, and by means of a double-acting spiral spring, is brought back to the neutral position as soon as the segment moves out of

Fig. 152
View of Operating Mechanism with Limiting Device for Pole Type Single-Phase Regulator

engagement, thereby allowing a re-engagement between the pawls *D* and the notched wheel *C*.

Operation

The operation of the mechanism is as follows: The relay should be adjusted by means of the variable resistance in series with the relay coil and the adjustable counter-balancing spring so that, with the desired voltage across the line controlled, the balanced arm *M* is horizontal. In this position of *M*, the triggers oscillate under and just clear the trip pins *FF*. This condition prevails as long as the voltage is within 1 per cent of that desired. Beyond this variation in voltage, however, the change in the pull of the relay coil causes the arm *M* to move sufficiently out of the horizontal position as to cause one of the trip pins *F* to interfere with its trigger *E*, causing pawl *D* to engage in the notched wheel *C*. This engagement constitutes a pawl and ratchet connection between the operating motor and the regulator armature, and the movement is continued

until the voltage across the line is again such as to bring the arm *M* to a horizontal position and the triggers *EE* again clear the trip pins *FF*.

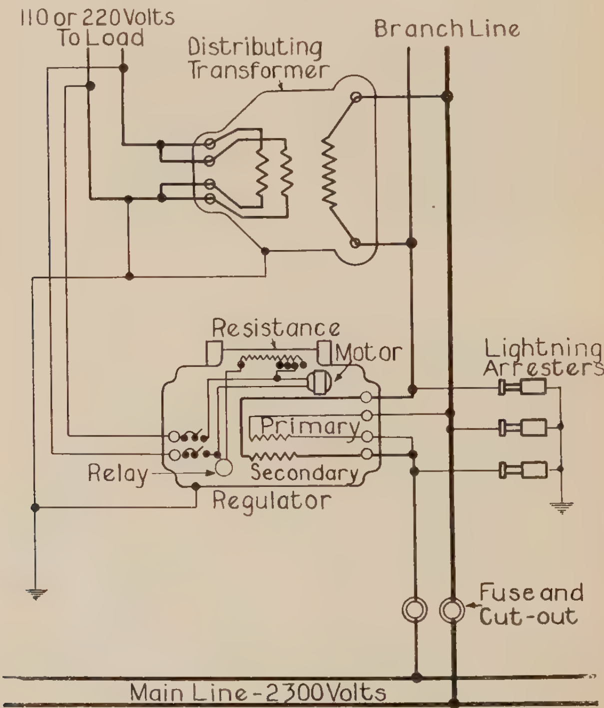


Fig. 153
Diagram of Connections of Pole Type Single-Phase Regulator and Distributing Transformer

As the regulator armature, and hence the notched wheel *C*, must be rotated in either direction, it is necessary to disengage pawl *D* at the end of each stroke. This is accomplished by the fixed projection *H* engaging with the lips on the under side of the pawls. At the end of each

stroke, each pawl is lifted sufficiently to engage with its trigger E, which trigger is tripped at the beginning of the stroke by the trip pin F if the voltage of the regulated feeder requires further adjustment, but which otherwise oscillates freely until a further regulation of the voltage is necessary.

As the regulator approaches either limit of rotation, the cam K approaches and rotates under the pawl driving the regulator in that direction, and raises the pawl by means of the pin L, thereby preventing any further engagement of that pawl with wheel C. This does not, however, prevent the regulator from being rotated in the opposite direction, during which rotation the cam K is again returned to its normal position by means of the spiral spring. In addition to this limit device, a positive stop is provided on the cover of the regulator to prevent the worm gear segment S from being turned out of mesh with its worm.

Special attention has been given to the lubrication of all wearing surfaces. The motor is provided with ball bearings which are lubricated through special grease cups. The gear for the motor worm runs in oil, for which the supporting casing forms a well, and the remaining bearings are waste-packed.

This design of regulator is built in one standard size only, the rating being 2.3 kv-a. when wound for 60 cycles and 2300 volts. When wound for a 20 per cent voltage range, that is, 10 per cent boost and 10 per cent lower, it will therefore regulate the voltage of a 23 kv-a. 2300-volt circuit within the established limits of 1 per cent if the voltage variation of the circuit controlled does not exceed the capacity of the regulator. The regulator can also be wound for lower frequencies, but this is attended by a corresponding reduction in size.

Fig. 154
2.3 Kv-a., 60-Cycle, 2300 Volts, 10 Per Cent, 10 Amp. Automatic Pole Type Single-Phase Regulator Installed

If larger regulators are required for outdoor service, the station design, arranged with a weatherproof casing for the operating and control mechanism, is recommended. A regulator with such an arrangement is shown in Figs. 169 and 170.

The time required to adjust the pole type of regulator from its maximum lowering to its maximum boosting position or vice versa is 1.5 minutes; this is somewhat longer than required by the standard station designs of regulators. The situations where the pole type design of regulator is used and the conditions under which it is used are not, however, so exacting as required or demanded by the business, residential and industrial centers, and its performance has therefore been entirely satisfactory.

The efficiency of the regulator is high considering its kv-a. capacity and the voltage for which it is wound. Based on impedance watts and core loss, the efficiency at 75 deg. C. is nearly 92 per cent at full load. The copper loss at full load (by wattmeter) is 160 watts, and the core loss is 60 watts.

This type of regulator being intended for pole mounting is subjected to the extremes of heat and cold. It is therefore very liberally designed regarding heating and is provided with a special oil, the freezing point of which is −30 deg. C. corresponding to 22 degrees below zero F. The oil becomes a semi-liquid at this temperature and does not solidify until a much lower temperature is reached.

The diagram in Fig. 153 shows the connections of the regulator and auxiliaries with reference to the line. The diagram shows the regulator control connected to the secondary of a distributing transformer. If it should be desired to control a feeder supplying a number of distributing transformers, the regulator may be mounted on the

same pole with the first connected transformer, or the control may be obtained from a small transformer having a capacity of approximately 300 watts. Fig. 154 shows a typical installation of this design of regulator, and Fig. 155 gives the overall dimensions and weight.

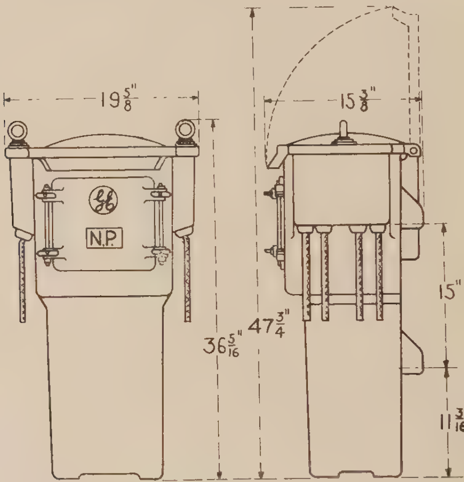


Fig. 155
Dimensions of Pole Type Regulator for 2300-Volt, 60-Cycle Circuit

FEEDER CAPACITY in Amp.	INCREASE OR DECREASE IN LINE VOLTAGE		KV-A.	NET WT. in Lb. (Approx.)	NO. OF GAL. OF OIL
	Per Cent	Volts			
10	10	230	2.3	550	5

SECTION XX

MINIATURE REGULATORS

The regulators so far illustrated and described are designed for controlling the voltage of distributing circuits, and their kv-a. capacity is therefore comparable with the kv-a. capacity of the generating or transforming apparatus in a generating station or substation. However, electrical energy is, to some extent, directly used in various industries as a source of heat for heat treatments, electrochemical processes, etc., and conditions occur which demand an accurate voltage control, frequently over a considerable range, and on circuits of comparatively small kv-a. capacities. The same requirements may also occur in laboratories and for some kinds of electrical testing.

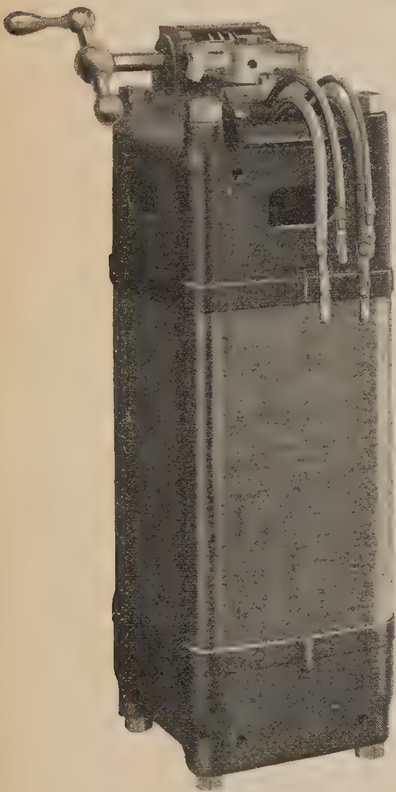


Fig. 156
Industrial Type Hand-Operated Regulator

To provide for such requirements, a small regulator designated as

the Miniature Type has been designed and a considerable number of them have been built.

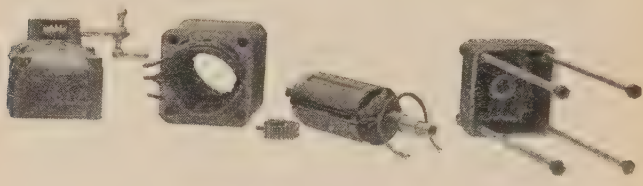


Fig. 157
Disassembled Industrial Type Hand-Operated Regulator

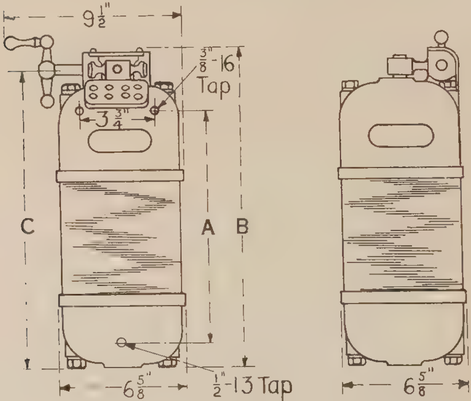


Fig. 158
Dimensions of Industrial Type Hand-Operated Regulator for 230-Volt 60-Cycle Circuit

FEEDER CAPACITY in Amp.	INCREASE OR DECREASE IN LINE VOLTAGE		KV-A.	DIMENSIONS IN INCHES			NET WT. in Lb. (Apprx.)
	Per Cent	Volts		A	B	C	
20	10	23	½	9 1/16	14 ⅛	13 3/16	75
30	10	23	¾	10 9/16	15⅝	14 11/16	85
40	10	23	1	12 1/16	17 ⅛	16 3/16	100
50	10	23	1¼	15 1/16	20 ⅛	19 3/16	125

In design and construction, this regulator is similar to the larger sizes, but it is arranged for hand operation only and for voltages which do not exceed 220. It is self-

Fig. 159
Oil Testing Set Consisting of a Transformer, Industrial Type Regulator and Spark Gap

cooled, but is not oil-immersed, and can be wound for either single-phase or polyphase circuits. This regulator is shown in Fig. 156. Fig. 157 shows it disassembled, while Fig. 158 gives dimensions and weights. For 60-cycle 110- or 220-volt circuits, this regulator can be furnished in sizes from 100 to 1250 watts, either single-phase or polyphase and for any voltage range. For lower frequencies, the kv-a. capacity is correspondingly reduced. For intermittent service, the rating may be increased depending upon the length of time the regulator is in service, as, for instance,

when used to control the primary voltage of a high potential testing transformer as shown in Fig. 159.

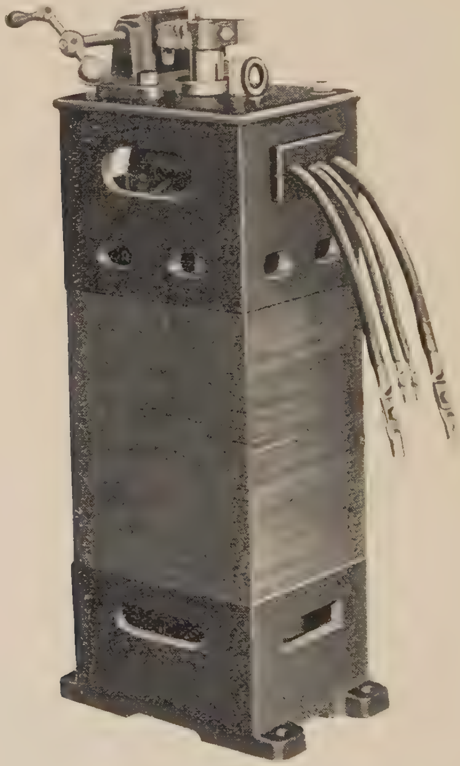


Fig. 160
Hand-Operated Single-Phase Regulator

For intermediate sizes between the miniature and the station types, a modification of the pole type design has been made. In this modified design, standard parts are used throughout with the exception of the end frames (or flanges) and the cover. This design is shown in Fig. 160.

It also is of the self-cooled (but not oil-immersed) design and is hand-operated. It is built for single-phase circuits only and for voltages from 110 to 550. For 60-cycle circuits,

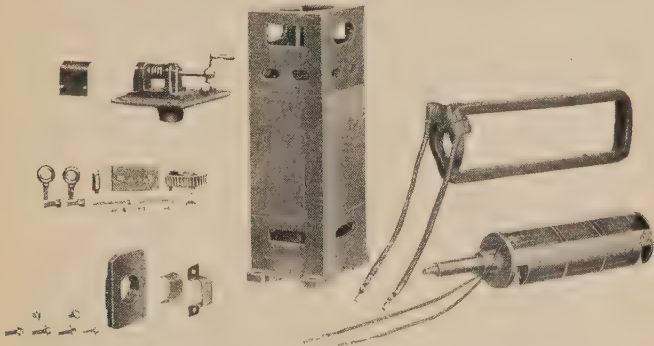


Fig. 161
Disassembled Hand-Operated Single-Phase Regulator

this regulator can be furnished in sizes from 1 to about 4 kv-a., and in smaller capacities, for the lower frequencies. Fig. 161 shows the general construction of this design, and Fig. 162 gives its dimensions and weights.

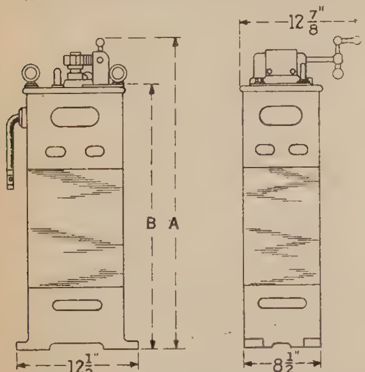


Fig. 162
Dimensions of Hand-Operated Single-Phase Regulator for 230-Volt, 60-Cycle Circuits

Feeder Capacity in Amp.	Increase or Decrease in Line Voltage		KV-A.	Dimensions in Inches		Net Wt. in Lb. (Approx.)
	Per Cent	Volts		A	B	
40	10	23	0.9	22⅝	17⅞	240
80	10	23	1.8	25⅝	20⅞	290
120	10	23	2.7	28⅝	23⅞	340
160	10	23	3.6	31⅝	26⅞	390

SECTION XXI

ADVANTAGES OF FEEDER VOLTAGE REGULATION

The primary object of all voltage regulation is either to supply a constant and predetermined voltage at the load or to vary the voltage as the nature of the load may require. Lamp and motor loads require a definite and uniform voltage for their most efficient and economical operation, whereas the industrial application of electrical energy—such as to furnaces, welding sets, and ovens—generally requires a variable voltage.

A constant voltage, or one sufficiently constant for all practical purposes, can be obtained at the load either by maintaining a constant bus voltage and designing the distributing feeders so as to have a negligible voltage drop or by compensating for the feeder drop and for bus voltage variations by means of a feeder regulator. However, a varying voltage to suit load conditions, if obtained from a constant voltage generator or bus, must always be obtained by some type of voltage regulator.

Continuity of service is generally recognized as the prime requisite in the distribution of electrical energy, and the quality of the service is next in importance. The value of an accurate voltage control naturally varies for different applications of power and is probably a maximum in incandescent lighting.

The percentage of the total power generated and used for lighting varies greatly for different generating stations, but the incandescent lamp is used to a much greater extent, and by a vastly larger number of customers, than any other electric energy consuming device. The illumination obtained from the incandescent lamp is also affected to a greater extent by changes in voltage than the performance

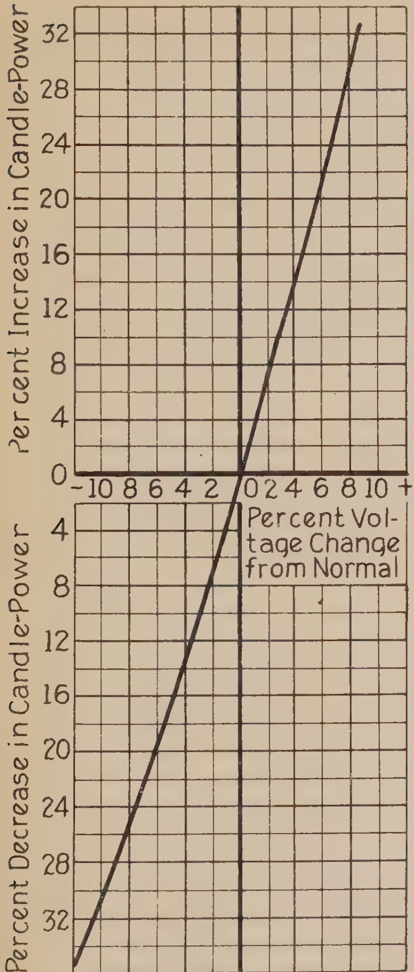


Fig. 163
Relation Between Candle-Power and Voltage of Mazda C Lamps

of other power consuming devices so that, due to its extended use and its susceptibility to voltage changes, the candle-power of the lamp is the general criterion whereby the public judges the efficiency of public service corporations supplying electric power.

Relation Between Candle-Power and Voltage

Fig. 163 illustrates the variation in the candle-power of the Mazda lamp at various voltages, and it will be noted that the former varies with the latter in the ratio of 3.5 to 1. It is generally considered that, for good service, the total voltage variation should not exceed 2 per cent. Yet, assuming 1 per cent voltage variation either way from normal, this corresponds to a change of

7 per cent in the candle-power. The 2 per cent variation considered is at the center of distribution of the feeder so that the variations at the lamp socket, due to the voltage drop in the secondary wiring, will be even greater. A total voltage variation of 5 per cent is not unusual and corresponds to a variation in candle-power of about 18 per cent.

Relation Between Cost of Power and Voltage

As the candle-power of the lamp changes at a greater rate than the applied voltage, it follows that the cost of illumination increases with voltages lower and decreases with voltages higher than normal. On the assumption that the cost per candle-power at 100 per cent rated voltage is also 100 per cent, the varying cost per candle-power for varying voltages is given in Fig. 164, and as is to be expected, the cost increases rapidly with a decreasing voltage. From the curve, it might be assumed that, as the cost decreases with increasing voltage,

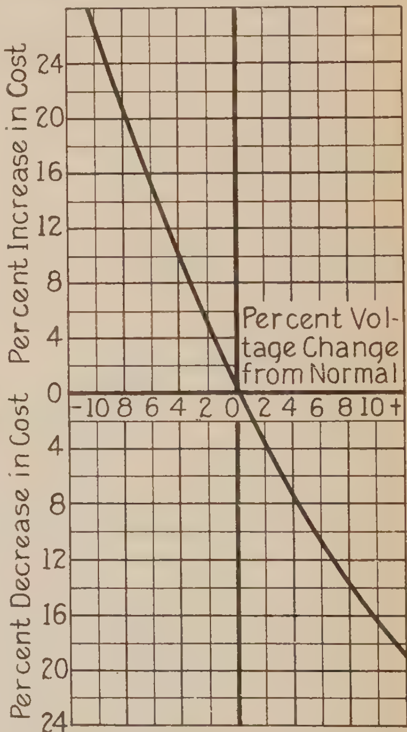


Fig. 164
Relation Between Cost of Illumination and Voltage of Mazda Lamps

it would be advisable to operate the lamps at a voltage higher than normal. The life of the lamp, however, decreases rapidly with an increase in voltage, and so more frequent lamp renewals are required. This increase in cost must be considered in the total cost of service. The normal voltage designated for the lamp is therefore based on the cost of the lamp, its average efficiency, and on the cost of power. While these figures may vary to some extent, it is recommended that lamps be operated at their designated voltage.

By comparing Figs. 163 and 164, it is apparent that with any voltage lower than normal (this is the prevailing condition) the ultimate consumer, that is, the general public, pays the highest price for the poorest service. Public opinion is of paramount importance and good will of incalculable value, and it is therefore essential that a uniform and proper voltage be maintained within reasonable limits on all lighting circuits. Furthermore, in addition to "Satisfied Customers", operating companies gain a material advantage from maintaining normal voltage at the lamp in the increase in the sale of power.

Relation Between Power Sold and Voltage

Fig. 165 shows the relation between the power taken by the Mazda lamp and the voltage applied. It will be noted that the power increases or decreases by approximately 1.6 per cent for each per cent change in voltage. If it is assumed that 1000 hours is the service of a lamp per year, that a 40-watt lamp is the average size, and that the selling price of power is 10 cents per kw-hr., then each per cent drop in voltage below normal represents an annual gross loss in revenue of 6.4 cents per lamp. On the assumption that the average voltage is 2 per cent low, this

represents a loss of 3.2 per cent to the central station in its lighting revenue.

If it is further assumed that the lighting load is only 20 per cent of the total load, and that the power load sells for 2.5 cents per kw-hr., the loss in the lighting revenue still represents 1.6 per cent of the total income. If the electrical installation is capable of carrying the small additional load at the peak occasioned by an increase of 2 per cent in voltage (that is, maintaining normal voltage), this 1.6 per cent loss on the gross income due to low voltage is not compensated for in any way by any saving in fixed charges or operating expense but only by the saving in the cost of fuel, and by the increase in the life of the lamp. The loss therefore represents a much higher percentage of the net income or dividend than indicated by the figure given.

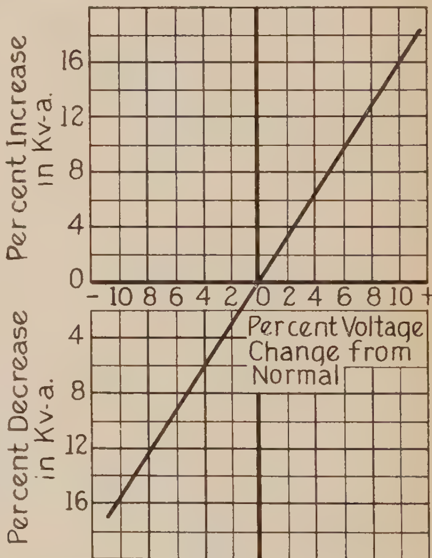


Fig. 165
Relation Between Voltage and Power Required by Mazda Lamp

Economy of Feeder Voltage Control

The loss considered cannot, however, be saved without an expenditure for a regulating equipment to compensate

for the voltage variation occasioning the loss. If a 150-amp. 2300-volt single-phase lighting feeder (that is, a 345 kv-a. circuit) be considered on the preceding basis, the gross gain in revenue per year is $1100.00. Assuming that a voltage regulator capable of maintaining normal voltage has a cost of $1200.00, that the fixed charges are 15 per cent, that the losses in the regulator are based on full load for 1000 hours and core loss for the rest of the time, and that the cost of these losses is chargeable at cost of power at the switchboard, then, at 1 cent per kw-hr., the total cost of the regulator including fixed charges is only $225.00 per year for the feeder considered. The additional power sold, due to the increase of 2 per cent in voltage, is 11,000 kw-hr. Assuming the cost of fuel at 0.5 cent per kw-hr., the actual net cost of this additional power would be $55.00. Assuming that the central station does not give free lamp renewals, the total cost of selling $1100.00 worth of additional energy from one 150-amp. 2300-volt single-phase feeder is $280.00. This leaves a net gain of $820.00 per year for an expenditure for the regulator of $1200.00, plus the installation charges.

A regulator of the size considered will have a voltage range of 20 per cent total. It will, therefore, compensate for all normal voltage variations of the bus as well as the voltage drop in the feeder due to varying load, and will insure a constant and predetermined voltage at the center of distribution of the feeder regulated.

Electric household appliances (other than motors) operated from lighting circuits require nearly as close a voltage regulation as the incandescent lamp. Appliances, such as flatirons, curling irons, warming pads, toasters, percolators, broilers, etc., are used to a large extent because of their convenience. In all of these appliances, the power

consumed, and hence the heating, varies approximately as the square of the voltage applied. A 5 per cent drop in voltage equals a loss of 10 per cent in power sold, that is, under low-voltage conditions less energy is used by the heating unit than that for which it was designed. Hence, unless the voltage is maintained approximately normal, the appliances lose their value as conveniences and dissatisfaction results.

A satisfied customer is, however, in this particular case, the best advertising medium for further sales of appliances and power, and since the sale of power is the ultimate aim in selling appliances, it is therefore of the highest importance to maintain the rated voltage.

Power supplied to household appliances should be exceedingly profitable and well worth soliciting; first, because such power is usually taken "off the peak" and requires no increase in the kv-a. capacity and hence in the cost of the plant, and the only increase in the operating expense is that for fuel; and, second, because this power is usually sold at the maximum or lighting rates (only the larger households being supplied with separate circuits for the power load).

Voltage Regulation and Illuminating Engineering

Extensive investigations have been made to determine the most economical and effective illumination for residences, places of business, street lighting, and for decorative purposes. Lamps of various sizes and designs and having various characteristics of light distribution have been designed and are being manufactured.

The designing of reflectors and distributors, as well as the proper selection and arrangement of the combination of lamps, reflectors and fixtures to produce the desired

effect, has become a science and the designing of lighting fixtures has become a fine art. Regardless, however, of how scientific or artistic the design and arrangement of the illuminants, the ultimate effects and results depend on a

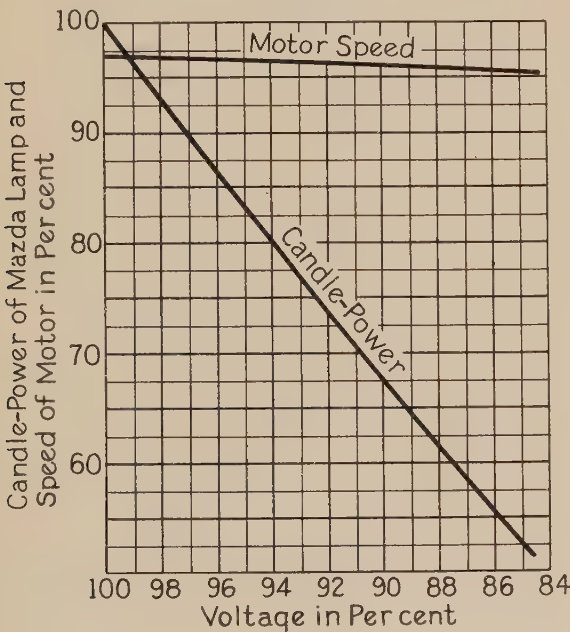


Fig. 166
Relation of Voltage to Speed of Squirrel Cage Induction Motor and Candle-Power of Incandescent Lamp

proper and uniform voltage at the lamp socket, and this can not be obtained economically without the use of automatically operated feeder voltage regulators.

Industrial Illumination

The illumination of factories and shops has been extensively investigated, but its importance relative to the

efficiency of the plant and the welfare of the operators is not generally appreciated. In manufacturing establishments operated by electric power, continuity of service, rather than a uniform voltage, is the prime requisite, for within certain limits, motor speeds are affected to only a small degree by comparatively large variations in the voltage, and work will progress even with variable or inferior illumination.

Fig. 166 shows the effect of a variable voltage on the speed of a squirrel cage induction motor and on the illumination of the incandescent lamp, and it should be noted that, although at a voltage of 10 per cent below normal the motor speed has changed only about 1 per cent, the illumination has decreased 33 per cent. In general, small changes in the speed of machine tools or other machinery are not of serious consequence other than decreasing the output by the per cent drop in speed; but if the operators depend on artificial illumination, the same drop in voltage may result in such poor illumination that the output may be decreased by a much greater amount and, in addition, the quality of the work may also be lowered.

Relation Between Efficiency of Operators and Illumination

Physical fitness and health are generally recognized as being essential to efficiency, but good eyesight and proper illumination are practically as important. Complaints as to eye-strain and headaches due to insufficient light are common. The effect of eye-strain on the general health, and therefore on the efficiency of the operator, thus becomes of the highest importance.

The cost of good illumination is an insignificant percentage of the wages paid to an operator. The amount and the quality of output of an operator are both increased

by proper illumination, and therefore the slight increase in cost occasioned by a change from poor to good illumination is certain to return enormous interest.

Safety First

The connection between illumination and accidents has been investigated by comparing the number of accidents occurring during periods of natural and artificial lighting, and the results indicate that, in general, the accident rate is much higher during the latter period than during the former. It is generally conceded that natural light is superior to such artificial illumination as usually provided. The obvious inference is that accidents can be greatly reduced by proper and adequate illumination.

Good illumination is conducive to cleanliness, better sanitary conditions, and the maintenance of the mental and physical health of operators. Then, too, the more favorable the conditions under which work is performed, the higher becomes the type of workmen attracted and the more permanent becomes their service.

Good illumination therefore increases the efficiency of operators and thereby increases the efficiency of the plant. This, in turn, increases the dividends which, from a purely materialistic viewpoint, is the prime consideration.

The general subject of illumination is an exceedingly broad one and includes the size and arrangement of windows for the admission of daylight, the arrangement of the work benches or machines, the nature of the walls with reference to reflection and absorption, as well as the arrangement of the illuminants for artificial lighting. The discussion of the effect of voltage regulation on the illumination produced by the incandescent lamp is therefore only one phase of an exceedingly important subject. It is, however, a very

important one where the incandescent lamp is the source of artificial light, for regardless of how scientific may be the arrangement of the illuminants, the results will be satisfactory only if proper voltage is applied at the lamp socket.

Economy in the Generation of Power

The economy of generating electric power by the use of large generating units, by establishing generating stations of great capacities, and in distributing this power at high voltages is generally recognized. The voltage of a generator or a number of generators in the same station may be automatically maintained constant, regardless of the load, at the station bus or at any one point on the transmission or distributing system by means of a generator voltage regulator, but this means of voltage regulation is unsatisfactory when several transmission circuits fed from a common bus supply power demands of varying character. The several lines may be of different lengths and resistances, and the power demand may occur at different times, so that the voltage delivered at various points may vary greatly unless each line is individually controlled. The ability to control the voltage of individual lines emanating from a generating station therefore allows the use of larger and more efficient units and thus simplifies the station equipment and reduces both the initial and operating costs.

Economy in the Distribution of Power

By controlling the voltage of the individual feeders emanating from a distributing station or substation, similar economies are possible. The various feeders may be designed to suit their particular requirements, and by their combination with the proper feeder voltage regulators,

each individual feeder may be supplied with the proper voltage at its center of distribution regardless of the demands on other feeders. With this arrangement, the high efficiency now obtained in the generation of power is obtainable in its distribution also. If the substation and distribution system are arranged as indicated, the regulator should have a sufficient capacity to compensate, not only for the variations in the voltage drop of the feeder controlled, but also for any variations in the substation bus voltage due to the varying voltage drop in the line from the generating station to the substation.

By controlling the bus voltage of the distributing station or by regulating the voltage of its individual feeders, a number of substations can be supplied by a single transmission circuit or by a network of interconnected circuits, and economies can often be effected by such arrangements. The ability to control the voltage of individual feeders therefore allows economies in the generation and distribution of power which are otherwise not obtainable.

Regulators to Reduce Line Investment

The choice between voltage regulators to compensate for the voltage drop in a feeder and an increase in the section of the line copper to decrease the drop depends on the relation between:

The cost of the regulator plus the cost of the losses in the regulator and in the line, and

The cost of additional line copper (sufficient to decrease the line drop to an allowable amount) plus the line loss.

Constant voltage can be maintained at the center of distribution by means of a regulator, but it can not be obtained by any increase in the line copper. The regulator will also compensate for the variations in the supply

voltage, whereas an increase in the line copper will in no way compensate for this voltage variation. The installation of a regulator will, therefore, be economical even if its total cost somewhat exceeds the cost of additional line copper required to maintain the voltage variations within reasonable limits.

Assuming, as an arbitrary illustration, a 100-amp. 2300-volt single-phase lighting feeder one mile long, and comparing the use of a line of one No. 000 wire and one of one No. 4 wire, and further assuming the difference in the cost of the line construction to correspond to the difference in the cost of the copper at $0.30 per pound (this cost including the increase in the line cost as a whole); then, on the basis of power cost at 1 cent per kw-hr. and with the load factor assumed, the following comparison applies:

Single-phase 2300-volt, 100-amp. feeder, one mile long.

Size of wire	(1 No. 000)	(1 No. 4)
IR drop in per cent	2.84	11.4
Loss in line in kw-hr. per year		
2 hr. per day at full load	4760	19150
2 hr. per day at ¾ load	2670	10200
2 hr. per day at ½ load	1190	4780
2 hr. per day at ¼ load	300	1190
Total	8920	35320

Feeder regulator recommended	7.5%
Kw. rating	17.25
Kw-hr. per year loss in regulator	
2 hr. per day at full load	570
2 hr. per day at ¾ load	325
2 hr. per day at ½ load	280
2 hr. per day at ¼ load	205
16 hr. per day at no load loss	1460
Total	2840

Cost of line at $0.30 per pound........	$1630.00	$403.00
Cost of regulator....................	......	900.00
Total cost	$1630.00	$1303.00
Saving in investment..................	......	$327.00
Total losses in kw-hr..................	8920	38160
Cost at 1 cent per kw-hr...............	$89.20	$381.60
10 per cent on investment...............	163.00	130.30
Total cost per year....................	$252.20	$511.90
Excess operating cost of No. 4 line per year.......		$259.70

The saving of $327.00 in investment does not justify the annual loss of $259.70.

Now, assuming, for the same load, a line two miles long and having the same voltage drop, this will require doubling the section of the line without making any change in the regulator. The comparison of costs then will be as follows:

	(2 No. 000)	(2 No. 4)
Cost of line at $0.30 per lb............	$6520.00	$1612.00
Cost of regulator.....................	....	900.00
Total cost	$6520.00	$2512.00
Saving in investment..................	....	$4008.00
Total losses in kw-hr.................	8920	38160
Cost at 1 cent per kw-hr..............	$89.20	$381.60
10 per cent on investment.............	652.00	251.20
Total cost per year..................	$741.20	$632.80
Excess operating cost of 2 No. 000 line per year....		$108.40

The cost of operating the unregulated line is now in excess of that of the regulated line by $108.40, and by using a regulator, the saving in the investment is now also very appreciable, being $4008.00. The total saving per year in favor of the (two No. 4) regulated line is, therefore, the difference between the operating cost in the two cases

considered, and amounts to $108.40. From this analysis it would seem that, in some cases, the cost of line construction as well as the cost of operation can be very appreciably decreased by using regulators.

The use of regulators to reduce line construction cost is not, however, the only consideration, for by their use, any variations in the bus voltage can be compensated for and a uniform voltage maintained at the center of distribution of each feeder, thereby increasing the sale of power and giving more satisfactory service to customers.

As indicated in the first tabulation, there may be no justification for the use of a regulator to decrease line construction cost for short lines, but as previously shown, their use may be more than justified by an increase in the sale of power. The use of various sizes of line copper so that each feeder will most economically satisfy the conditions of service may be objectionable from a standardization viewpoint. The objection is undoubtedly justified in congested districts where the feeders are short or where underground feeders are used, for in underground feeders, the decrease in the size of copper is limited by the heating of the conductors, this heating depending on the number of conductors per cable as well as on the cross section of the conductors. It would, however, seem that for overhead lines—and especially for suburban lines of some length—economy could be obtained by the use of smaller line copper, or copper-sheathed wire, and feeder regulators.

SECTION XXII

THE APPLICATION OF THE INDUCTION REGULATOR

Feeder voltage regulators have generally been considered to be of value mainly for the control of lighting feeders, and while this has to a large extent been true, they are being required to a much greater extent than formerly for the control of industrial, power, and transmission circuits.

The impression that the requirement of accurate voltage regulation is limited to the control of lighting circuits is undoubtedly due to the absolute dependence of the incandescent lamp on a proper voltage for satisfactory results and to the fact that the voltage regulator was originally developed and used exclusively for this purpose.

In general, the accurate voltage control of lighting loads is still of greater importance than a close voltage regulation of power loads, but there is an increasing number of situations where the accurate control of the voltage of circuits supplying loads other than lighting is of the highest importance. As indicated in the preceding sections, the induction voltage regulator has been developed and standardized to such an extent that regulators built of standard parts are now available for practically every requirement.

Voltage Control of Lighting Circuits

The use of the induction voltage regulator for the control of the voltage of lighting feeders has become so universal that their use might almost be considered as the general practice of modern stations. The importance of such voltage regulation is indicated in the preceding section and by the fact that various cities and states have enacted ordinances and laws regarding the allowable voltage

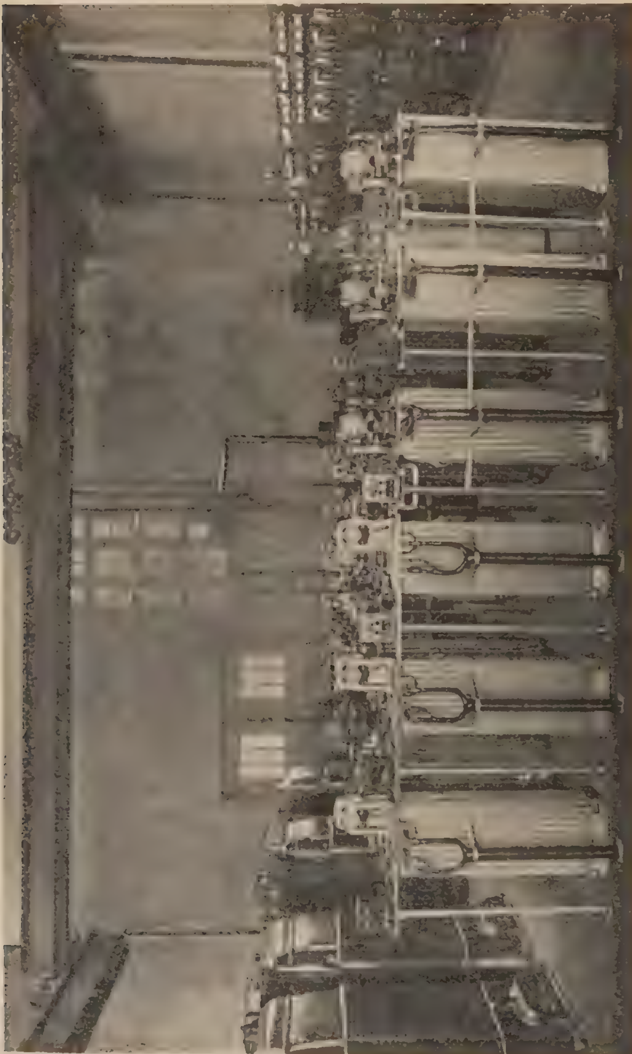


Fig. 167
Single-Phase Feeder Regulators Installed by the Commonwealth Edison Co., Chicago, Ill.

variations. These have been summarized in Circular No. 56 of the Bureau of Standards, issued by the Department of Commerce, Washington, D. C.

For the most efficient and satisfactory service, the load on the feeder should be concentrated as much as possible, as indicated in Fig. 143.

A concentration of load or the establishment of a center of distribution with reference to each feeder is generally possible and feasible in densely populated sections, but is prohibitive wherever a single feeder is required to supply a large area. The two conditions may, however, be considered and treated similarly, and nearly as efficient and satisfactory service can be obtained from the latter as from the former.

For all conditions, the generation of power is concentrated as much as possible and distributed to centers of distribution. In the larger cities, these centers are substations from which the power is again distributed to secondary centers.

Feeder Control

In alternating-current distribution, each feeder supplying these secondary centers is generally controlled by a voltage regulator. The substations usually contain no rotating machinery. Their equipment generally comprises: the step-down transformers, the lightning arresters, the distributing board, and the automatic feeder regulators. Typical illustrations of this type of station are shown in Figs. 167 and 168.

Regardless of the number of feeders emanating from a substation, or of the varying demands on the individual feeders, if each feeder is controlled by an automatically operated regulator, only a single attendant is required, and

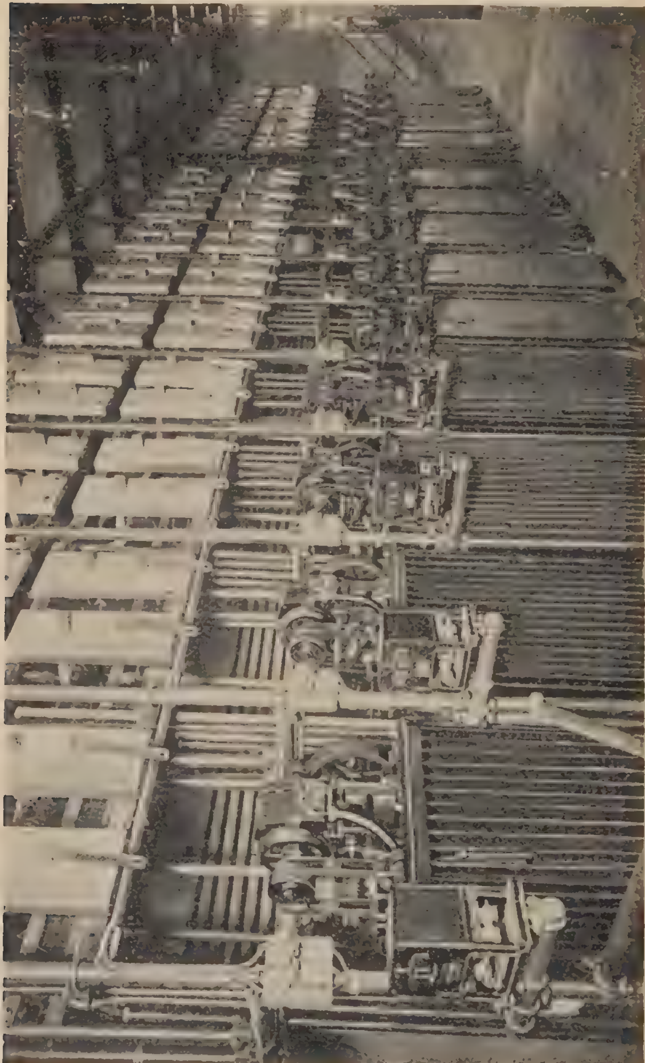


Fig. 168

Single-Phase, 60-Cycle, 2300-Volt, 10 Per Cent, 150 and 200 Amp. Automatic Induction Regulators Installed by the Louisville Gas and Electric Co., Louisville, Ky.

in some cases, the substations have no regular attendant but receive only periodical inspection.

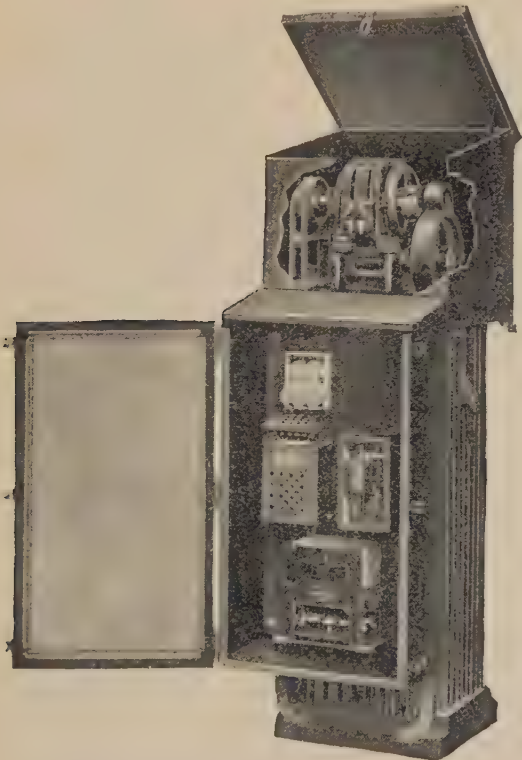


Fig. 169
Outdoor Type Single-Phase Regulator

Synchronous Converters

In direct-current distribution for lighting, the area served is usually restricted and the individual feeders are not separately controlled but are interconnected so as to

equalize the voltage. Each synchronous converter is, however, usually operated from its own bank of trans-

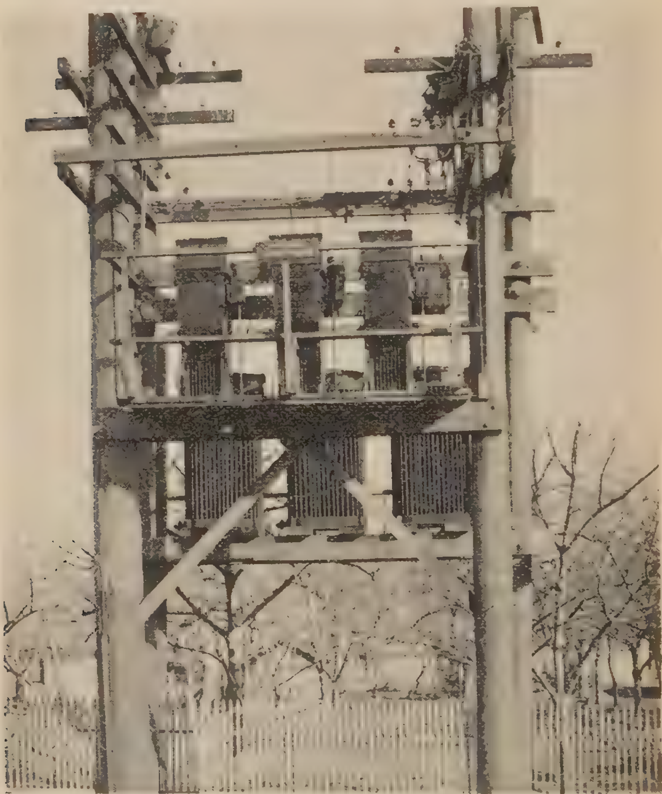


Fig. 170
Three $34\frac{1}{2}$ Kv-a., 60-Cycle, 2300-Volt, 10 Per Cent, 150-Amp., Single-Phase Automatic Outdoor Regulators Installed by the Northwestern Electric Co., Portland, Ore.

formers, the secondary voltage of which is varied by means of a polyphase induction regulator of the design illustrated

in Fig. 56, or by a series booster. The method used for regulation necessarily depends on initial and operating costs.

Branch Feeder Control

In the extension and interconnection of power systems and in the absorption or elimination of the isolated plant, it is not possible at the station to control the voltage of the resulting long lines of feeders so as to satisfy the various demands all along the interconnecting or transmission line.

If a single feeder supplies a large area, regulators should be installed to control the branch feeders, as indicated in Fig. 143. The pole type of regulator was designed for this particular class of service, and for the control of larger feeders than can be regulated by this design, the station type arranged for outdoor service is available. Fig. 169 shows a standard station type of regulator provided with a weatherproof sheet iron casing so arranged that all parts of the mechanism and of the control are readily accessible. An installation of this design of regulator is shown in Fig. 170.

Voltage Regulation of Bus of Transformer Substations

As power can be generated much more economically by large generating units, isolated plants are being eliminated and transformers are being substituted for the generating apparatus installed. The distribution of the power supplied by isolated plants is, in a good many instances, limited to a small area so that the individual voltage control of the various feeders may not be required. The bus voltage is, however, usually controlled by some form of generator voltage regulator. After substituting transformers for the generating equipment, the same voltage regulation can be obtained by controlling the voltage of the bus by a single

induction voltage regulator. This regulator should, however, be installed in the converted transformer substation as the line supplying this substation may also supply other substations.

Industrial Lighting

The previous section calls special attention to the desirability of accurately controlling the illumination in manufacturing establishments. Factories operated by electric power usually purchase their power at power rates which are very much lower than lighting rates. Such power is, however, generally unregulated, and the lighting load is therefore subjected to voltage variations, allowable for power loads, but detrimental to illumination. The defect can, however, readily be remedied by the installation of a feeder voltage regulator to control the voltage of the lighting feeder only.

If the lighting installation is comparatively small, or even if it covers a considerable area, the pole type of regulator is admirably suited for this purpose. It can readily be wound for 110- or 220-volt or for 110/220-volt three-wire distribution. If this design of regulator is too small, any of the standard designs of the station type can be adapted either for indoor or outdoor installation and can be wound for either the primary or secondary supply voltage.

Voltage Regulation of Power Circuits

A feeder regulator should be installed if the power is variable and if the voltage variation in the line due to the variations in power or in the supply are detrimental to the service.

Regulators used to control power circuits are generally of the polyphase design and of the larger sizes, and the

increase in their use has been very appreciable during the last few years. If the power circuit supplies a single customer, the regulator controlling the circuit is preferably installed in the generating station or substation from which

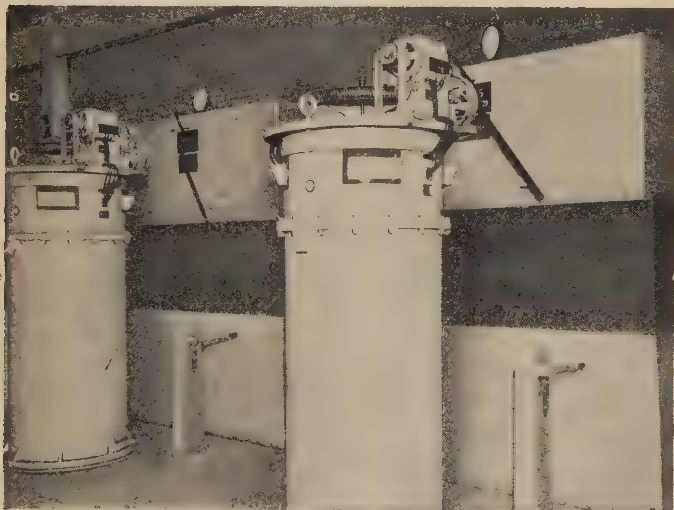


Fig. 171
Three-Phase, 600 Kv-a., 60-Cycle, 2300 4600-Volt Primary, 230 460-Volt Boost and Lower, 1500 750-Amp., Motor-Operated Regulators Installed by the Detroit Edison Co., Detroit, Mich.

the feeder emanates, but if a single circuit serves several customers, the regulator must be installed at some point between that at which the power is taken from the line and that at which it is used by the customer, that is, it should be installed in the branch line which supplies the customer whose power requires voltage regulation.

The voltage regulation of feeders supplying power to customers at some distance from the generating station is

particularly desirable because of the economies introduced by the decrease in the cost of line construction as indicated in the previous section. Besides, it is of decided value to the customer.

Regulators of all sizes and wound for various voltages are available for these requirements as indicated in Figs. 89 to 93 inclusive, and if not already developed, they can usually be built of standardized parts to suit almost any condition or requirement of operation.

Fig. 171 shows two 600 kv-a. regulators of the air-blast design in a modern distributing station. Many more of this and smaller sizes are installed on the same system.

Voltage Regulation of Industrial Circuits

Electrical energy used as power in manufacturing operations does not usually require voltage regulation unless the motors used are of the induction type and a constant and uniform speed is required, as, for example, in weaving. Electrical energy used as such, as in electrical processes, usually requires an accurate voltage control which frequently must extend over a wide range. Under this heading may be included electric furnaces of various types, electric welding and heating, and electrochemical and electrolytic processes.

Arc furnaces do not require an accurate voltage control external to the furnace as the length of the arc is adjustable and power is thereby controlled. Furnaces of the induction type depend, however, on an accurate voltage regulatoin of the supply circuit. This must be obtained either by the field control of the generator or by means of a feeder regulator. The larger induction furnaces are controlled by regulating the field of the generators which supply the energy; but the smaller sizes, supplied from feeder circuits,

are regulated in part by induction regulators. Hardening and annealing furnaces in which the heat is produced by current passing between two electrodes and through a bath consisting of various kinds of salts require very accurate voltage control as does also the resistance type in which the crucible and its contents or the object requiring heat treatment is placed within a chamber containing resistance units.

The resistance furnace has a wide application extending from its use for obtaining very high degrees of heat sufficient to melt the more refractory materials to its use for providing the lower heat required for enameling ovens. Accurate temperature control requires accurate voltage control, and the induction regulator has been used to some extent for this purpose. Such regulators have ranged in size from 100 watts in the miniature design to 200 kv-a. in the standard station type.

Electric contact welding (whether spot, butt or line welding) requires a close voltage regulation as do also heat treatments obtained by passing the current through the material treated. The induction regulator has been used for the voltage regulation necessary for such heat treatments and, wherever used, has given satisfaction.

In the electrochemical industry, the induction regulator has been extensively used, as not only is an accurate voltage required but one which is variable over a wide range. Electrochemical processes conducted on a commercial scale usually require a large amount of energy at a low voltage. Fig. 172 shows a single-phase regulator removed from its tank, and having a current capacity of 10,000 amperes and a voltage range of from 83 to 237. A number of regulators of this particular size are in use in various electrochemical industries, and orders for their duplication is ample evidence of their worth.

Due to the range in voltage required, it is sometimes economical to obtain the voltage control by the combination of a regulator and a transformer, the ratio of which transformer is also variable by means of taps and switches.

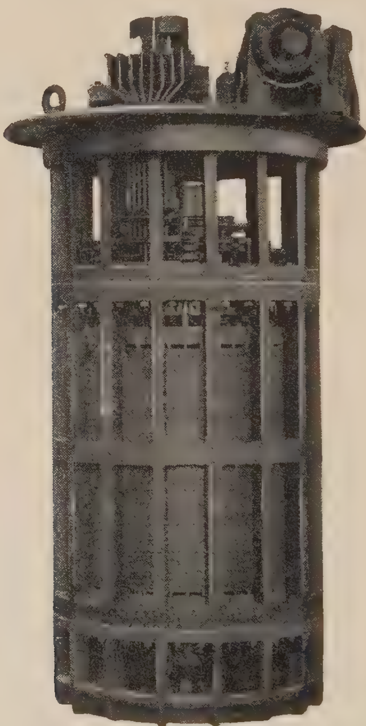


Fig. 172
Induction Voltage Regulator Removed from Tank

This combination is, however, more complicated, requires more attention, and has a higher cost of upkeep, so that the first cost alone should not be taken as the basis of

comparison. If continuity of operation is essential, the likelihood of interruption becomes less as the design of the regulating equipment becomes simpler.

When the power used for electrolytic work is obtained from a synchronous converter, the polyphase induction regulator affords a very convenient means for obtaining voltage control. This combination may have a somewhat higher initial cost than a motor-generator set, but the efficiency of the former is usually higher than that of the latter so that, if there is a difference in initial cost, the efficiency or operating cost should be considered in connection with the initial cost as a basis for comparison.

Adjustment of the Voltage of Interconnected Systems

The division of the power delivered by two or more interconnected alternating-current generating systems depends on their kv-a. capacities and on the adjustment of their prime movers, and is independent of their voltages. The magnitude and the angular displacement of the current delivered by each interconnected generating station depends in part on the impedance of the interconnecting line, and on the voltages at the stations.

With a given voltage and current, the relation between the power and the kv-a., that is, between the energy current and the total currents, delivered by any station is indicated by the power-factor. For instance, at 80 per cent power-factor, the power current is only 80 per cent of the total current, whereas the wattless current is 60 per cent. These two currents are at right angles to each other, and, added vectorially, constitute the load current as indicated by the ammeter.

The relation between the power current and wattless current delivered by any station feeding an interconnected

system is governed by the adjustment of the voltages at the various stations, and while voltage regulation will not reduce the total wattless current required by the system, any desired division of this current among the various generating stations feeding the system can thereby be obtained. The voltages of the several generating systems must be equalized or adjusted not only to distribute the wattless current properly, but also to prevent the needless circulation of wattless current due to improper voltages.

If a generating station supplies power for local distribution and is interconnected with other generating stations, and if, for the local distribution, it is desired to maintain a constant voltage or one of predetermined value depending on the load, it is economical and generally necessary to have the voltage of the interconnecting feeder variable independently of the bus voltage so as to adjust the wattless current to the best advantage. The proper division of this wattless current is of considerable importance because the load capacity of the generators with regard to heating, the voltage drop both in the generators and in the lines, and the generator and line losses are all affected by it. This subject is treated more fully in the following section.

The induction regulator has been used very successfully for adjusting the voltage of interconnected systems. It has, however, so far been necessary to use motor-operated regulators, for no suitable and reliable power-factor indicator of the contact-making type has been developed. In considering regulators for this class of service, it should be borne in mind that the object of the regulator is the adjustment of the wattless current, that is, the adjustment of the power-factor. The adjustment is

therefore determined by means of a power-factor indicator connected between the station bus and the regulator.

Fig. 173 shows a 1000 kv-a., 11,000-volt, three-phase regulator used, for the purpose described, in a 70-mile

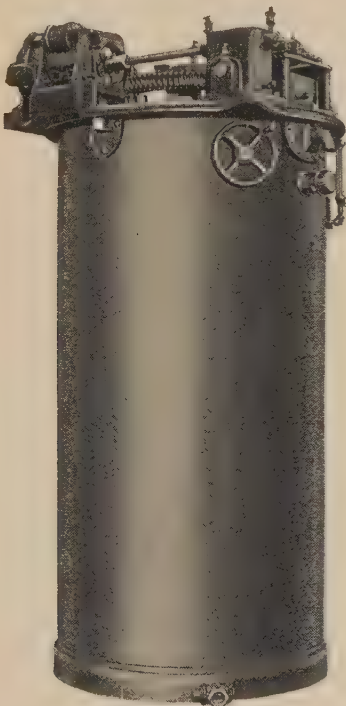


Fig. 173
Three-Phase Oil-Immersed Forced-Oil Regulator

66,000-volt transmission line connecting a steam- and a water-power generating station. The regulator is in the steam plant and is connected in the low-tension side of the transformers.

In applying regulators to transmission lines, it is desirable that they be connected in the low-tension side of the transformers because of the limitations in the voltage for which regulators can be wound and insulated.

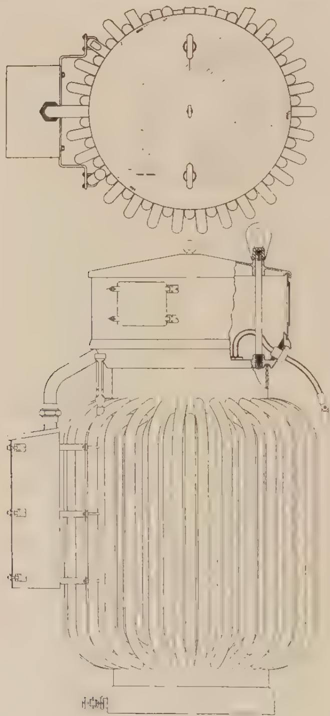


Fig. 174
Automatic Self-Cooled Outdoor Type Regulator

In the multiple operation of direct-current generating stations and alternating-current sources of supply through synchronous converters, the induction regulator has been successfully applied. In case the alternating-current power

is purchased on a maximum demand basis, or if derived from water power and the maximum output is desired (the variations in the power demand being supplied by a

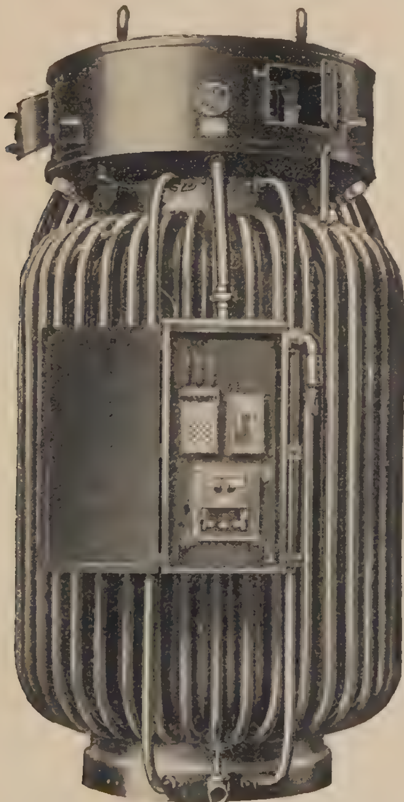


Fig. 175
Automatic Oil-Immersed Self-Cooled Outdoor Type Polyphase Regulator

steam-driven plant), the regulator can be automatically controlled by a contact-making ammeter in the alternating-

current supply circuit, thereby insuring a constant and predetermined amount of power from the alternating-current source.

The larger sizes of regulators are also arranged for either indoor or outdoor installation similar to the sizes used for the control of lighting feeders. Figs. 174 and 175 show a 600 kv-a. regulator and illustrate the typical arrangement.

Miscellaneous Applications

The induction regulator is used almost exclusively to control the voltage of high-potential testing sets. The testing transformer is wound for twice the line voltage, while both the primary and secondary of the regulator are wound for the line voltage. A potential gradually varying from zero to twice the line voltage can thus be applied to the low-tension winding of the transformer thereby varying the voltage across the high-tension winding.

The induction regulator also finds extensive use in the calibration of instruments (both voltmeters and ammeters) and in various other testing and laboratory work. In fact, this type of regulator is applicable wherever accurate voltage regulation is required whether the circuit to be controlled has a capacity of 1 kw. or 10,000 kw.

SECTION XXIII

THE FUNCTION OF THE INDUCTION REGULATOR IN THE INTERCONNECTION OF POWER SYSTEMS

The interconnection of two or more alternating-current generating systems is fundamentally identical to the parallel operation of several generators in the same station, and the same conditions apply to assure their proper operation with regard to the distribution of the load and the power-factor of the load on the individual units.

The division of the load between two or more direct-current generators operated in parallel depends upon the voltage adjustment of the individual generators and on the supply of power to their prime movers, whereas the division of power between alternating-current generators is independent of the former and dependent only on the latter.

The power delivered by either a direct-current or alternating-current generator is equal to the product of the armature current times the terminal voltage times the cosine of the angular displacement between the two. In direct current, the angular displacement is always zero and the cosine of the angle is 1, whereas in alternating current, the angular displacement may vary between zero and 90 degrees, the cosine varying between 1 and zero.

This can be illustrated by considering the current flowing through a resistance. If the resistance is ohmic only, the current flowing through the resistance is in phase with the voltage (for either alternating or direct current) and the power in the resistance is equal to their product. If, however, the resistance is reactive only and the current is alternating, the current is at right angles to the voltage and the power is therefore zero.

The armature of any generator may be considered as the resistance with the voltage internally generated or applied. The total resistance in the circuit is that of the armature considered, the resistance of any other parallel connected armature (which is in series with the first armature when considering a circulating current due to an excess of voltage in one of the armatures), and the resistance of the load also in series with the first armature.

The resistance of a direct-current circuit is always ohmic resistance only, whereas in an alternating-current circuit, the resistance is always a combination of ohmic and reactive resistance. Current in a direct-current machine, therefore, always represents power. In an alternating-current machine, it represents power only if it is in phase with the voltage or is represented by that component of the current which is in phase with the voltage.

The following conditions therefore apply in the two cases.

Increasing the field excitation of one of two parallel-operated direct-connected generators increases the voltage necessary to overcome the resistance of the armature and thus causes more current to be supplied by that armature. The circuits through which this current tends to flow are the load circuit and the circuit through the parallel-connected generator. The current supplied to the load is, however, determined and limited by the resistance of the load and the voltage at its terminals, and the flow of current through the parallel-connected generator is opposed by the voltage generated in its armature and by its resistance, the resistance voltage being in phase with the generated voltage.

Increasing the voltage of one generator causes an increase in the bus voltage depending, however, on the

kv-a. capacity of this generator relative to the other generator connected in parallel with it. Increasing the voltage adjustment of one generator must therefore increase the load on that generator and cause a corresponding decrease in the load on the parallel-connected machine. The increase in the load on the higher-voltage generator reduces the speed of that generator. This reduction in speed causes the governor of the prime mover to act and to admit more steam or water to the prime mover and, hence more power to the generator, and thus enables it to supply a greater load.

If the prime mover and generator considered have sufficient kv-a. capacities, increasing this generator voltage so as to exceed the no-load voltage of the other generator will produce a reversal of the current in the second generator and cause it to operate as a motor. The generator with the high excitation will then deliver more power than demanded by the load, but whatever the current distribution, the currents and voltages are always in phase. The power in any direct-current machine is therefore always the product of the current flowing in the armature and its terminal voltage.

Increasing the field excitation of one of two parallel-operated alternating-current generators also increases the voltage necessary to overcome the resistance of the armature and thus also causes more current to be supplied by that armature. The circuits through which this current tends to flow are, as already stated, the load circuit and the circuit through the armature of the alternator connected in parallel.

The current taken by the load is likewise determined and limited by the resistance, or rather by the impedance of the load, and by the voltage at its terminals as in the

direct-current distributing system. The flow of current through the parallel-connected alternator is opposed by the voltage generated in its armature and by the resistance of that armature as in a direct-current machine. The resistance offered by the armature to the flow of an alternating current is, however, almost entirely reactive; hence, a current may flow through the armature which current will be practically at right angles to its terminal voltage, the armature in this respect functioning as a reactance connected across the alternator having the higher excitation. The value of this current will be equal to the excess voltage generated in the first alternator divided by the sum of the impedances of the two alternators, and it will flow through the parallel-connected generators as a circulating current.

As the current due to the excess voltage in one generator is at right angles to the terminal voltages, it is wattless. In other words, increasing the voltage on one of several parallel-connected alternators does not increase the power supplied by that alternator except by the amount necessary to overcome the ohmic resistance of the circuit through which the excess current flows.

Due to the sine wave current and voltage characteristics of alternating-current generators, it is essential that the speed of all alternators connected to a common bus or system be identical, that is, the angular speed per pole must be identical. An increase in the excitation of one alternator will increase the current output of that machine as in the direct-current generator, but this increase in the armature current does not represent an increase in the power supplied by that armature as in the direct-current machine for the reason that in an alternator the current due to the excess voltage has an angular displacement from the voltage of nearly 90 degrees, the cosine of which angle

is zero. There is therefore no tendency for the armature so loaded to change its speed; hence, no action of the governor of the prime mover results. The adjustment of the governor

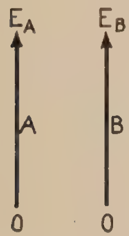


Fig. 176

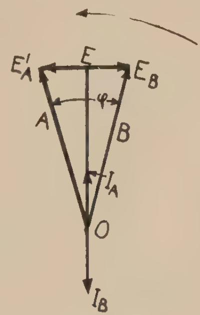


Fig. 177

Figs. 176 and 177
Vector Voltage Diagrams of Two Parallel-Connected Alternators at No Load

of the prime mover must, however, in this case also be depended upon for the distribution of the load among a number of generators, the action being as follows.

Alternator Phase Displacement Necessary to Cause a Shift of Load

Assuming two identical alternators mounted on the same shaft so as to have no angular displacement between like poles, and assuming that these alternators are excited identically, it is evident that their voltages E_A and E_B will be equal and in phase, as indicated in Fig. 176. If the alternators are connected in parallel by connecting them to a common bus, no current will therefore flow through the windings. If, however, the alternators are keyed on the shaft so that they are displaced in phase by an angle φ as shown in Fig. 177, a resultant voltage is produced by this displacement, as E'_A E_B.

This voltage, it should be noted, is nearly at right angles to the voltages induced in each alternator. This resultant voltage causes a circulating current to flow through the two armatures, and as the resistance to the flow of current is almost entirely reactive and only a small percentage is ohmic, the current caused by this resultant voltage will be nearly at right angles thereto, as OI_A and OI_B.

This current has therefore a relatively small angular displacement from the alternator voltages OE'_A and OE_B, but it is evident that, while it is nearly in phase with one alternator voltage, it must be as nearly opposite in phase to the voltage of the other alternator. As the product of the armature current and the terminal voltage of the alternator times the cosine of the angular displacement between the two represents power, it is therefore evident that one alternator must act as a generator and the other as a motor.

The phase relations can, therefore, probably be better illustrated by making use of the synchronous motor diagram, bearing in mind, however, that the voltage of the motor is always shown as opposite to that of the generator. That is, if two alternators are connected in parallel and are in phase and both act as generators, the voltage diagram is then as indicated in Fig. 176; but if, without any change in the angular displacement or in the excitation, one of these alternators is considered as a motor, the voltage diagram is then as in Fig. 178. On this basis, Fig. 179 is a reproduction of Fig. 177. The resultant voltage is E_R and the resultant current is I_R. As previously stated, this current is determined almost entirely by the reactance of the alternators. It must therefore lag behind E_R, that is, it is nearly in phase with the voltage E'_A and as nearly

opposite in phase to the voltage E_B. The alternator A which has been forcibly advanced, therefore acts as a generator and delivers power to B as a motor.

In the case considered, no external work is being done. If the alternators were free to move relatively, the load on

Fig. 178

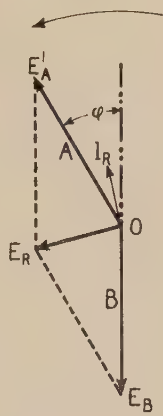


Fig. 179

Figs. 178 and 179

Vector Voltage Diagrams of Two Parallel-Connected Alternators at No Load

A would retard A and the power supplied to B would accelerate B until they would assume a relative position practically equal to Fig. 176 or 178 in which position the current would be zero. The resultant current I_R may therefore be considered as the power exchange or "pull in" current which tends to maintain parallel-connected alternators in phase and which holds them in synchronism.

For the purpose of this discussion, the alternators are, however, not free to move relatively, and the electrical energy supplied by A to B is used by B as mechanical

energy to drive A. The losses are supplied by the engine driving the shaft on which A and B are mounted.

As both alternators are connected to a common bus, it is evident that their terminal voltages must be equal. It

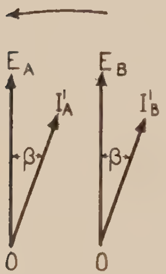


Fig. 180

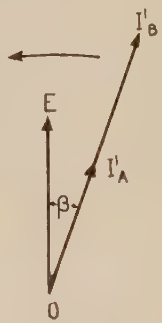


Fig. 181

Figs. 180 and 181
Vector Current and Voltage Diagrams of Two Parallel-Connected Alternators

also is evident that, the alternators being identical, one-half of the resultant voltage E_R represents the voltage drop in each alternator due to the current I_R. These voltage drops are necessarily equal and opposite, and the terminal voltage of each alternator is therefore the resultant of the induced voltages OE'_A and OE_B respectively, and the voltage drop EE'_A, and EE_B respectively or OE, that is, OE in Fig. 177 is the voltage at the terminals of both alternators.

If a load is taken from the common bus to which A and B are connected, and the total load current supplied to the line is equal to $2I$, then, if the alternators are in phase as in Fig. 176, they respectively will supply, to the line, currents which are equal in value and equally displaced from the voltage, as shown in Fig. 180. As the voltages

E_A and E_B as well as the currents I'_A and I'_B are in phase, the total load may be represented as in Fig. 181.

If under this line load condition, the armatures are displaced in phase as assumed in Fig. 177, the generator

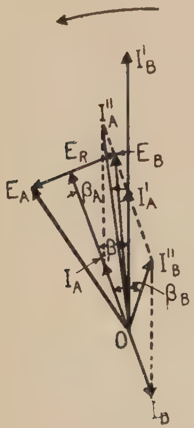


Fig. 182

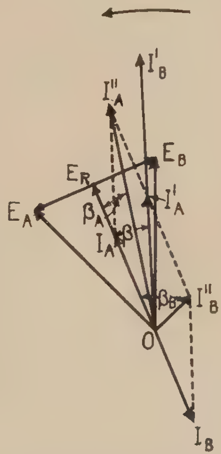


Fig. 183

Figs. 182 and 183
Vector Current and Voltage Diagrams of Two Parallel-Connected Alternators

load currents will become unequal, the current OI_B (Fig. 177) being deducted vectorially from the current OI'_B (Fig. 180), and the current OI_A (Fig. 177) being similarly added to OI'_A (Fig. 180). The resultant relations of the currents and voltages in the two alternators are given in Fig. 182.

The load taken from the bus in Fig. 182 is the same as in Fig. 181 and the displacement between the bus voltage OE_R and the load current $OI'_A\ I'_B$ in Fig. 182 must, therefore, be identical to that assumed in Fig. 181. In other

words, angle β in Fig. 182 is equal to β in Fig. 181. The current supplied by A is now, however, I''_A and the current supplied by B is I''_B although the resultant or the vectorial sum of these two currents is still $OI'_A\ I'_B$. That is, the current supplied by the alternator A which was advanced is much greater than that supplied by B.

If E_A be still further advanced, as in Fig. 183, the load delivered to the line remaining the same as before, the exchange currents I_A and I_B are increased in proportion to the increase in the resultant voltage between E_A and E_B. Combining these increased currents with the original load currents given in Fig. 180 further unbalances the current distribution of the two generators. The advanced generator now delivers a much greater current than before, and the lagging generator, a smaller current. As E_R is the terminal voltage of each alternator, it also is evident from Figs. 182 and 183 that the power-factor of generator A has been increased and the power-factor of generator B has been decreased.

Although Figs. 180, 181, 182 and 183 show how a load may be distributed in any desired proportion among a number of generators by a fixed phase displacement of the generators, each generator is in practice driven by its own prime mover, and any phase displacement desired is obtained by a proper adjustment of the governors of the prime movers, and hence any predetermined load distribution can be thus obtained. The governors of the prime movers must, however, be such as to give a drooping speed characteristic as shown in Fig. 184, and they must be individually adjusted as conditions may require.

If it is desired to divide the load equally between two alternators, both governors must be identically adjusted as in Fig. 184, but if, for instance, one generator is to carry

twice the load of the other, the governors must be adjusted as in Fig. 185. If the load is to be carried proportionally by the generators, the governors must be adjusted so that at

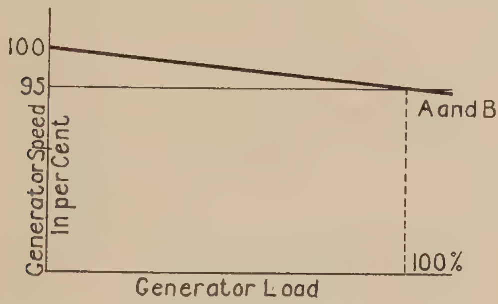


Fig. 184

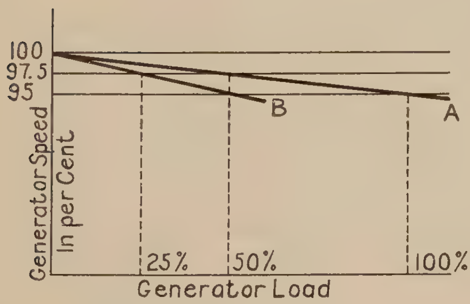


Fig. 185

Figs. 184 and 185
Speed Characteristics of Prime Movers for A-C. Generators

zero load the speed of the generators will be identical as shown in Figs. 184 and 185. As the load increases, the speed drops and the governors admit more power to the prime movers, but only in proportion to the load to be carried by each generator.

It is obvious that the generators must operate in synchronism. If, therefore, generator *A* in Fig. 185 should tend to operate at a higher speed than generator *B*, the advance in the phase position of *A* immediately increases its load and decreases the load on *B*. The speed of *A* is therefore retarded and the speed of *B* is accelerated until they are again equal. In Fig. 184, each generator drops in speed by the same amount for an equal increase in load; whereas, in Fig. 185, the speed of *A* is identical to the speed of *B* when *A* carries twice the load carried by *B*.

In view of the comparatively great change in the division of the load carried by parallel-connected alternators due to a small change in their angular displacement and because of the drooping speed characteristic of the prime mover, it is evident that any number of alternators will operate in multiple and that any predetermined part of the load can be carried on any generator. It also is now evident that the distribution of the load is determined by the mechanical phase displacement of the alternators and that this phase displacement is determined by the adjustment of the governors of the prime movers.

As is evident from the preceding discussion, the prime movers of parallel-connected generators must have drooping characteristics. The change in the frequency due to the change in the speed under different load conditions may, however, be objectionable and prohibitive. A speed correction is therefore made by means of a current relay connected in series with the load. This current relay controls a small motor whereby the initial adjustment of the governor is changed with changes in the load.

In Figs. 184 and 185, for instance, it is desired to operate at 100 per cent speed when the generator load is 100 per cent. The current relay causes the governor to be

adjusted so that the generator would operate at 105 per cent speed at no load if the load were instantly removed, that is, with this setting of the governor, the generator

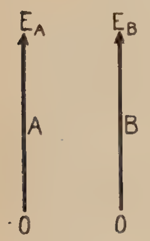


Fig. 186

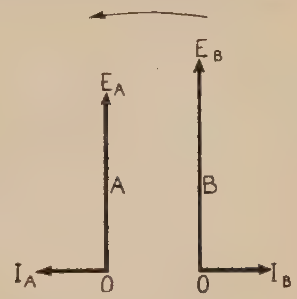


Fig. 187

Figs. 186 and 187
Vector Diagram Illustrating the Effect of Unequal Excitation of Parallel-Connected A-C. Generators

will operate at 100 per cent speed at 100 per cent load. As the load changes, the current relay automatically readjusts the governor so that by means of this arrangement the generator operates at the same speed regardless of the load. Changes in the initial adjustment can thus be automatically obtained so that the proper frequency as well as the proper load distribution is maintained for all conditions.

Effect of Unequal Excitation on Parallel-Connected Alternators

If two identical alternators, driven by separate prime movers, are connected to a common bus and the alternators are equally excited and if no load is taken from the bus, then under this condition, the alternators will be in phase for the reasons already given, and no current will flow. This condition may be represented by Fig. 186.

However, if the excitation of alternator B is increased as indicated in Fig. 187, then this excess voltage causes a current to flow, and as in the case previously considered, this current is practically at right angles to the voltage causing it, as OI_B. The voltage causing the current is, however, in phase with the induced voltage of the generator as distinguished from the resultant voltage OE_R (Fig. 179) which is practically at right angles to the alternator voltage. The current OI_B (Fig. 187) is therefore now a wattless current and not a power current as it was in Fig. 179.

This current is necessarily equal and opposite in direction in the two alternators, as shown in Fig. 187. It is lagging with respect to the voltage in generator B and leading with respect to the voltage in generator A.

It has been assumed that the two alternators are connected to a common bus; hence their terminal voltages must be identical instead of as shown in Fig. 187. The wattless circulating current is directly proportional to the voltage causing it. The lagging current in B lowers the voltage of B but the leading current in A, being directly opposite in phase to the current in B, increases the voltage of A. In other words, a lagging current produces the same effect on the voltage as decreasing the field excitation, whereas a leading current produces the opposite effect or is equivalent to an increase in the field excitation. Since, in the case considered, the alternators are identical, the terminal or common voltage of the two machines is the mean of E_A and E_B. It should be observed that, as the circulating current in the present case is wattless, there can be no exchange of power; that is, a change in the excitation of one alternator cannot cause a phase displacement between the two machines, and it cannot, therefore, cause a shift in the load from one alternator to the other.

If, under the conditions assumed in Fig. 186, a load is taken from the bus, the load currents in the generators are equal, as shown in Fig. 180. However, if the excitation is unequal as in Fig. 187, the wattless current caused by the unequal excitation combines with the load currents as indicated in Fig. 188. In this diagram, the total load current $OI'_AI'_B$ is identical to the total load current in Figs. 180 and 181. The wattless currents OI_A and OI_B are identical to those given in Fig. 187. The resultant current in generator A is OI''_A and in generator B it is OI''_B. It will be noted that the current in A is less, and the current in B is greater, than in Fig. 180, although the actual power output is identical for each alternator for both conditions.

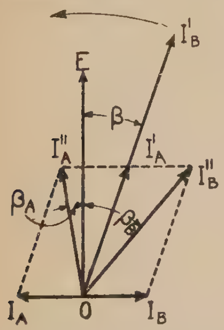


Fig. 188
Vector Diagram Illustrating the Effect of Unequal Excitation of Parallel-Connected A-C. Generators

OE is the voltage common to both alternators. The power-factor of A is therefore cosine β_A and the power-factor of B is cosine β_B. That is to say, the power-factor of A is higher than before and leading, and the power-factor of B is lower than before and lagging more than with an equal excitation of both generators. For an equal kilowatt output, the losses in B are therefore greater than in A. As the rise in the temperature due to the armature current determines to a large extent the maximum output, machine A, under the conditions assumed and for the same heating, can carry a greater actual load than machine B, although both have the same rating.

The maximum output with a minimum loss is obtained by operating both alternators at the same power-factor, that is, at the power-factor of the load.

In considering the shifting of the load in direct-current and alternating-current systems, it should be remembered that, in direct-current machines, the resistance to the flow of an exchange current resulting from a difference in the excitation is ohmic resistance only, that is, the exchange current is in phase with the voltage and their product therefore represents power. In alternating-current generators, the resistance to the flow of the exchange current is almost entirely reactive. The exchange current is therefore practically at right angles to the voltage causing it.

If the exchange current, or a component of this current, is in phase with the terminal voltage, as in a direct-current machine, and as may be produced by an angular displacement of the rotor or stator of the alternators, an exchange of power is obtained; that is, power may be transferred from one alternator to another. If, however, the exchange current is at right angles to the terminal voltage of the alternator, as obtained by changing the excitation, their product is zero and no transfer of power can take place. In other words, in the case of both direct-current and alternating-current machines, the transfer of load is obtained only by an exchange current which is in phase with the terminal voltage of the machine, and (as shown by the diagrams) this can be accomplished in alternators only by a shift in the angular displacement of a rotor or stator, and is in no way affected by changing the excitation.

The Interconnection of Generating Systems

As has been previously stated, the interconnection of two or more alternating-current generating systems is fundamentally identical to the parallel operation of generators in the same station, and the same conditions

apply for their proper operation. If two duplicate and equally excited generators are operated in multiple and are supplying power to a common bus, and if one generator has an ohmic resistance or a reactance, or a combination of

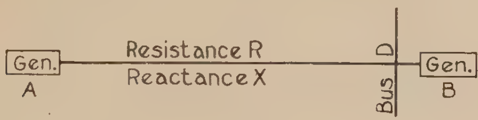


Fig. 189
One-Line Diagram of Two Interconnected Generators

both (such as the resistance and reactance of an interconnecting line) connected in series with it, it is necessary to adjust the voltage of that generator so as to compensate for the voltage drop across the series resistance or reactance in order to avoid the circulation of a wattless current which would otherwise flow.

If two identical generators (*A* and *B*) are arranged as in Fig. 189 and the entire load is taken from the bus *D* and if the governors of the prime movers are adjusted so that the load will be equally divided, then at no load and with equal excitation on both alternators the voltages will be in phase as in Figs. 176 and 186 and no exchange current will flow. As soon, however, as load is taken from the bus, the current flowing in the interconnecting line lowers and shifts the phase relation of the voltage of generator *A* at the bus *D*. The lowering of the voltage and its phase displacement depend on the impedance of the line, on the current flowing, and on the power-factor of the load supplied by the bus and by generator *B*. Assuming 100 per cent voltage, 100 per cent load, 100 per cent power-factor of load on the bus, that *B* is operating at 100 per cent power-

factor and that the voltages of generators A and B are E_A and E_B respectively as shown in Fig. 190, then the voltage of A at the bus D due to the resistance R and the reactance X of the interconnecting line, is E_D, that is E_D is the effective voltage of generator A at the bus D.

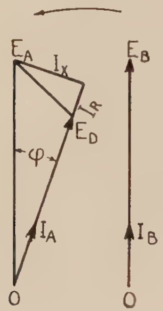


Fig. 190

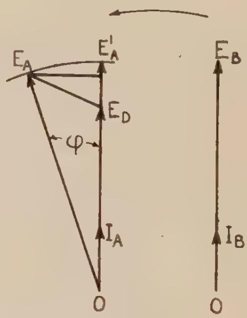


Fig. 191

Figs. 190 and 191
Vector Diagrams Showing Voltage Drop in an Interconnecting Line, and Compensation and Adjustment Required

The phase displacement between E_D and E_B (angle φ) causes an exchange of power; that is, the generators are initially unequally loaded. As, however, the governors of the prime movers are adjusted for equal load conditions, the condition of unequal loads will exist only until the exchange power supplied by B to A (the former being ahead of the latter in angular position) can pull A into phase as shown in Fig. 191. As shown, the voltages are, however, still unequal. This causes an exchange of wattless current, and to eliminate this current, it is necessary to increase the voltage E_D to be equal to E_B, as E'_A.

A similar condition exists for any power-factor of load; but as the power-factor decreases, within certain limits and

depending on the line constants, the voltage compensation required to eliminate the exchange of wattless current increases.

From Fig. 191, it will be observed that, under the conditions given and under load, the generators themselves are no longer in phase but that their effective voltages at the bus D are in phase. The phase displacement between the generators depends on the load, the power-factor of the load, and on the resistance and reactance of the interconnecting line. With, however, E_D increased in value to be equal to E_B and in phase with it, both generators deliver an equal amount of power to the bus D, but, as shown, due to the impedance of the connecting line, generator A operates at a lower power-factor (cosine φ) than generator B which operates at 100 per cent power-factor.

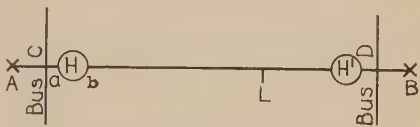


Fig. 192
One-Line Diagram of Two Interconnected Generators with Regulators in the Interconnecting Line

The Function of Voltage Regulators in Interconnected Systems

If all the power of generators A and B in Fig. 189 is delivered to the bus D, the voltage of A can be increased to compensate for the line drop by increasing the field excitation of A; but, if both A and B deliver power to individual buses (as in Fig. 192), and if it is desired to maintain a constant voltage on each bus and also to have either generator supply power to either or both buses, it is necessary to adjust the voltage between the buses by means of some type of feeder voltage regulation, as at H or H'.

Division of Wattless Current

Practically all alternating-current loads are more or less inductive and therefore require a lagging wattless current component, as, for instance, the magnetizing current of transformers and induction motors. As has been shown, a change in voltage of either generator causes wattless current to flow, the generator of higher voltage supplying the lagging current. If, therefore, the generator or bus voltages are to remain constant, an adjustment of voltage by means of a regulator in series with the interconnecting line will cause the lagging or magnetizing current to be supplied by either generator, or either generator may be caused to supply any desired percentage of this wattless current as indicated in Figs. 187 and 188. With a load of a given power-factor, one generator may therefore be operated at 100 per cent power-factor, that is, at its maximum efficiency, and another generator may furnish all the wattless current, that is, it may operate at a lower power-factor and at lower efficiency, or the wattless component may be distributed in any manner found most economical or desirable.

If, for instance, one generator is steam-driven and another waterwheel-driven, it may be desirable to supply the maximum output in power from the latter, and the wattless component from the former so as to economize fuel, or, if all of the generators are steam-driven, it may be desirable to supply the wattless current by means of a synchronous motor used as a condenser as outlined in Section XXVII, so that all of the generators may be operated at their maximum possible output and efficiency. If the bus voltages are required to be maintained constant, the distribution of the wattless component must, however,

be obtained by a voltage adjustment or regulation external to the generators, and any method of voltage regulation is applicable for this purpose.

It was shown that a change in the voltage of an alternating-current generator does not produce any change in the power supplied by that or any other generator; hence, the function of the regulator is solely to obtain a proper distribution of the wattless current component, that is, for the regulation of the power-factor of the load on the various generators.

Fig. 192 indicates that the regulator may be installed in either station *A* or station *B*. The location of the regulator depends somewhat upon the voltage requirements of intermediate points on the transmission line and upon the design of the step-up transformer with respect to its over-voltage capacity. However, in general, it is preferable that it be installed in the station from which the power transmitted is supplied so as to avoid having the line carry the exciting current of the regulator.

Regulators used specifically for the control of the power-factor of interconnected generating stations cannot be depended upon for the voltage control of the load taken at intermediate points on the connecting line. Assuming a load taken from the line at *L* in Fig. 192, if power is sent from *A* to *L* or to bus *D*, and if *A* is to supply the wattless component, the voltage must be equalized at bus *D*. The regulator at *H* must therefore raise the voltage at its *b* terminal by an amount somewhat greater than the line drop from *C* to *D* and the voltage at *L* will therefore be higher than at *C* or *D*.

If *B* is to supply the wattless component, the voltage must be equalized at the *b* terminal of the regulator *H*, that is, the regulator must lower the voltage of *A* at *b*

by an amount equal to the line drop. The voltage at L will then be lower than at C or D. If power is sent from B to L or C, and if B is to supply the wattless component, the regulator H must lower the voltage so that the voltage at its b terminal is somewhat less than the voltage of C minus the line drop, and the voltage at L will be less than at C or D.

If A is to furnish the wattless component, the regulator must boost the voltage, again giving a higher voltage at L than at either C or D. It also is evident that the voltage at L will depend on its relative distance from C and D and also on the relative amount of power supplied by A or by B. A similar condition exists with the regulator installed at H'. The voltage at any point on an interconnecting line is therefore dependent on the distribution of the load among the various generators and on the adjustment and location of the regulator for the control of the power-factor.

The Action of the Polyphase Induction Regulator When Connected Between Two Generating Stations

As illustrated in Section IV, voltage regulation by means of a polyphase induction regulator is produced by a phase rotation of the secondary voltage of the regulator, this voltage having a constant numerical value for all positions of the armature. In the voltage control of a feeder, this characteristic has no particular significance; but, when using this design of regulator in an interconnected system, it is desirable to investigate its action on the generators supplying the system.

In considering two interconnected generators or generating stations A and B (Fig. 192) with a polyphase regulator H' in the interconnecting line, the no-load voltage conditions may be represented by Fig. 193. The

diagram is drawn to scale for a 20 per cent regulator. E_A represents the voltage of generator A, and E_B represents the voltage of generator B before the introduction of the regulator (see Fig. 186). The voltage of the regulator connected in series with the interconnecting line has, however, a constant value, which is variable in direction as $O'R$, $O'E'$, $O'R'$ or $O'E''$ and, therefore, in order to equalize the voltages of generators A and B, the regulator must be rotated into position E' or E'', the former representing a right-handed and the latter a left-handed rotation of the regulator voltage from its maximum position $O'R$. The voltage of generator A at the bus D will therefore become either E' or E'', both displaced from the voltage of generator B, that is, E_B by the angle φ. This phase displacement between the voltages of the two generators causes an exchange of power as illustrated in Fig. 177, but as the generators are mechanically independent of each other, this power exchange pulls them into phase, after which the resultant of the generator voltage E_A and the regulator voltage $O'E'$ or $O'E''$ will be in phase with E_B after which no further exchange current can flow. That is, after generator A has automatically adjusted itself with regard to its phase position to generator B, it will occupy the relative angular position of E' or E'' depending on whether the regulator voltage was rotated in a right-handed or a left-handed direction. The resultant of the generator voltage and the regulator voltage at the bus D will, however, in either case be equal in value and direction to E_B, that is OO'.

Now assuming that the generators are loaded; that the entire load is taken from the bus D (Fig. 192); that the power-factor of the load is 100 per cent; and that generator A is operating at 100 per cent power-factor, also that

generator A is to supply a current of I_A and that the load requires a current of I_L, then the voltage E_A and current I_A of generator A are in phase and in the direction E_A

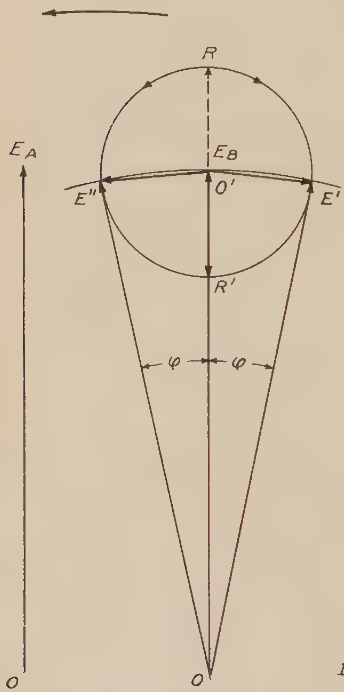


Fig. 193

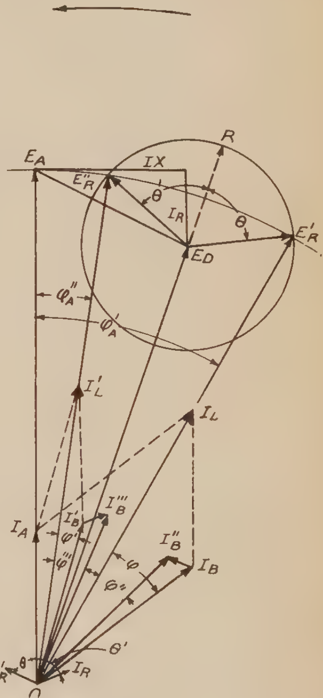


Fig. 194

Figs. 193 and 194
Vector Diagrams Illustrating the Effect of a Polyphase Regulator in an Interconnecting Line

(Fig. 194). The voltage drop in the line due to the flow of current from generator A to bus D is indicated by E_AE_D in Fig. 194. The voltage of generator A at bus D is therefore

E_D in value and direction. In order to equalize the voltages of the two generators, the regulator at H' may be rotated either to the right or left as $E_DE'_R$ or $E_DE''_R$. The resultant of the voltage of generator A at the bus D (that is, E_D) and the regulator voltage is therefore either E'_R or E''_R. The former is displaced from the voltage of generator A by the angle φ'_A and the latter by the angle φ''_A.

At no load and without the regulator, the voltage of B coincides with that of A (Fig. 186). These voltages must continue to be identical at some given point on the interconnection and under all conditions of load. This point has been assumed as at bus D. The assumptions already made fix the voltage of generator A with respect to its current I_A at the bus C and, therefore, generator B must shift so that its voltage coincides with E'_R or E''_R. As the total load current has been assumed as I_L or I'_L and the power-factor of the load has been assumed to be 100 per cent, generator B must deliver to the load either the current I_B or I'_B and at a power-factor of cos φ or φ' respectively. From the diagram it will be observed the angle φ is much greater than φ'; hence with the regulator rotated to the right, the power-factor of the energy supplied to the load by generator B is much lower than when the regulator is rotated to the left.

However, under the conditions imposed, generator B must also supply the primary current for the regulator. As heretofore shown, the current in the primary winding of the regulator is always proportional to the current in the series winding but varies in its angular position thereto directly as the mechanical position of the rotor to the stator varies. This is illustrated by Figs. 15 to 19 inclusive.

The current in the series winding of the regulator is I_A in value and in direction. As the regulator has a boost or

lower of 20 per cent, the numerical value of the current in the primary winding of the regulator is 20 per cent of I_A. With the primary of the regulator in its maximum boosting position as at R, the current in the primary winding would be in phase with the current in the series winding. However, in the case considered, the primary of the regulator has been shifted from its maximum boost position by the angle θ or θ'; hence, the current in the primary winding of the regulator is out of phase with the current in the corresponding series phase windings as I_A by the same angular displacement. That is, I'_R and I_R represent the currents in the primary winding of the regulator in value and in the correct angular position respectively for a right-handed or left-handed rotation of the regulator, the direction of the rotation of the currents in the primary winding being opposite to the direction of the rotation of the voltage induced in the series winding.

Respectively combining the current in the primary of the regulator, I'_R and I_R, with the current delivered to the load by generator B, I_B and I'_B gives the total current I''_B or I'''_B delivered by generator B. The resulting power-factors are cos φ'' or φ''' indicating that regardless of the direction of rotation of the regulator, generator B operates at the same power-factor.

Fig. 194 is not absolutely correct in that, for simplicity of illustration, the magnetizing current of the regulator has been omitted. However, the magnetizing current is comparatively small so that the diagram is sufficiently correct for all practical purposes and serves to illustrate the results obtained by the introduction of the regulator.

However, with regard to the regulator, the method of determining the direction of its rotation so as to give the best results is given in Section VI, and is illustrated in Fig. 36.

From the preceding discussion, it will be observed that the phase displacement introduced by a polyphase regulator is in no way detrimental to the operation of generators connected through a single transmission line but that the generators automatically adjust themselves so as to compensate for the phase displacement introduced, that the adjustment of the regulator determines the relative power-factor at which the interconnected generators operate, and that the division of the load on these generators is determined by the adjustment of the governors of their prime movers.

Determination of the Size of Regulator Required

The kv-a. capacity of the regulator required for the interconnection of generating stations depends on the reactance of the line, the load to be transmitted, the power-factor of the load, and the power-factor at which the generators are to operate. The impedance of the line expressed in ohms is constant, and, therefore, the actual voltage drop varies in numerical value in direct proportion to the current flowing. However, the power-factor of the load and the distribution of the wattless component between the generators connected, determine the power-factor of the load on the line and, hence, the direction of the actual voltage drop with reference to the generator voltage. The power-factor, as well as the load, must therefore be considered in calculating the line drop. The method of procedure can probably be best shown by several illustrations.

Case I

Assuming an interconnection between two generating stations consisting of a step-up and step-down transformer

and a transmission line, as shown in Fig. 195, each having a resistance and reactance voltage drop as indicated and as

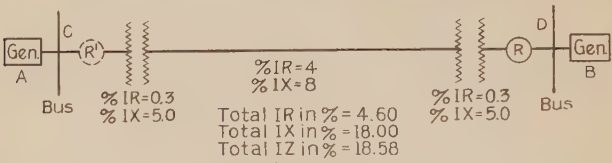


Fig. 195

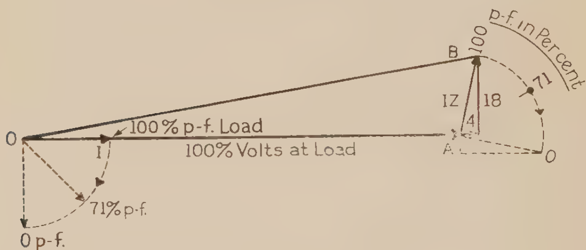


Fig. 196

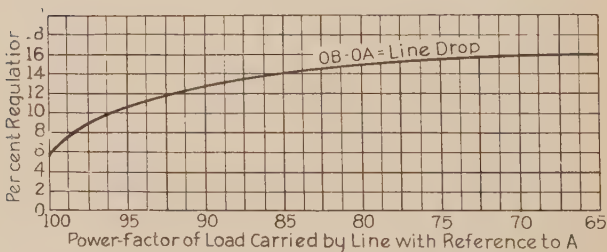


Fig. 197

Figs. 195 to 197

Diagrams Illustrating Voltage Regulation Requirements on an Interconnecting Line for Loads of Various Power-Factors

expressed in per cent for 100 per cent current, the regulation of the transmission line may then be determined as shown in Fig. 196, and expressed as shown in Fig. 197. The investigation is based on current load rather than on power load

for the reason that the heating of the transformers is the limiting feature; that is, for the same heating, the lower the power-factor of the load the smaller is the amount of power which can be transmitted; the kv-a., however, remaining constant.

From Fig. 196 it will be observed that the amount of voltage regulation required for varying power-factor loads depends on the relation between the ohmic and the reactive resistance drops of the transmission system. Fig. 197 indicates the rapid increase in the voltage compensation required as the power-factor of the load decreases.

In applying the above investigation to actual practice, the resistance and the reactance of the transformers are usually obtainable from the specifications furnished with the transformers, but the line resistance and reactance must be determined from tables found in all standard data books on electrical transmission. In order to determine the size of regulator required, the distribution of the load and the distribution of the wattless component between generators A and B must now be considered, and for illustration, the following conditions will be investigated. It should, however, be stated that, if each generator supplies power to the distributing bus at the power-factor demanded by the load, Figs. 196 and 197 give the size of regulator required, that is, if the transmission line is regarded as a feeder only, then the load supplied to any other station may be considered independently of the load supplied by any other generator assisting in the power supply, and the size of the regulator required is determined in the same manner as for any independent and isolated feeder supplying power.

In the following investigation, Figs. 198 to 201 inclusive have been drawn to scale, using the line constants

given in Fig. 195. The size of the regulator cannot, however, be determined graphically because of the difficulties in making sufficiently accurate drawings even to a scale larger than that used. The diagrams are given to indicate the general method of procedure rather than to solve the particular cases considered. To determine the size of the regulator for any given condition, the problem should therefore be solved mathematically, the line and load constants being substituted in the diagram in place of the general designations used. It is, however, desirable to draw the diagram to scale, not only because a better appreciation may be obtained as to operating conditions, but also to the end that the scale diagram may be used as an approximate check on the calculations.

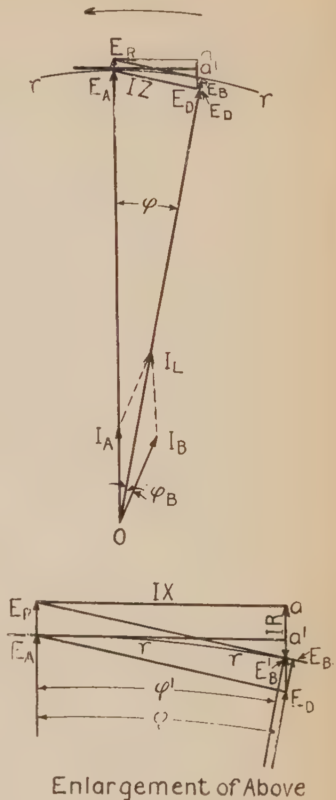


Fig. 198

Vector Diagram Showing Voltage Drop in an Interconnecting Line Due to Varying Adjustments of the Power-Factor of the Connected Generators

Condition 1

Assuming a 100 per cent power-factor load, the entire load being taken from bus *D*. Generators *A* and *B* are of equal capacity and each is supplying its full-load

current. The voltage drop in the transmission is as given in Fig. 195. Both generators operate at the same voltage, that is, the voltages at the buses C and D are equal. A operates at 100 per cent power-factor.

The diagram is given in Fig. 198. E_A is the terminal voltage of generator A. As the power-factor of A is 100 per cent, the line resistance and reactance drops are laid out respectively in phase with and at right angles to E_A, E_Aa' being the reactance and $a'E_D$ the resistance drop of the line. If the regulator is installed at R, the voltage of A at the bus D is E_D in value and in its angular position. E_D must therefore be increased in value to E_A, that is, to E_B. The regulator must therefore increase the voltage by E_DE_B. Generator B, in phase with E_A at no load, must now shift so that its voltage is in phase with E_D, that is, generator B must operate at a power-factor equal to cosine φ_B and lagging. It should be noted that the power-factor on the transmission line is leading (cosine φ), and that the voltage required of the regulator is even less than the IR voltage drop in the line, the former being E_DE_B and the latter E_Da'. This condition is more fully illustrated in Figs. 292 and 293. If the regulator is installed in position R' (Fig. 195) the following conditions apply:

The voltage of generator A at the bus D must be equal to E_B, that is, it must be on the arc r-r. The voltage drop triangle $E_Aa'E_D$ is therefore moved upward until the point E_D is on the arc r-r. The extension of E_A to E_R is then the voltage required of the regulator, and the voltage of B is E'_B. In this position, the regulator is a trifle larger but the power-factor of B is a trifle better than when the regulator is located in position R. However, this change in the position of the regulator increases the voltage on the

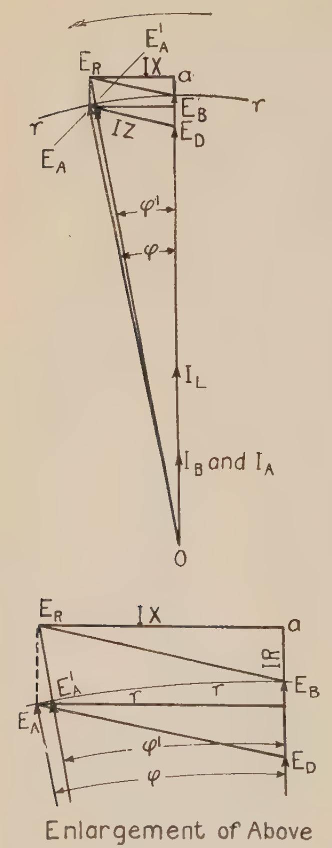


Fig. 199
Vector Diagram Showing Voltage Drop in an Interconnecting Line Due to Varying Adjustments of the Power-Factor of the Connected Generators

step-up transformers connected to bus C and may be objectionable for that reason.

Condition 2

Assuming the same conditions as in Condition 1 except that generator B operates at 100 per cent power-factor, the diagram for this requirement is given in Fig. 199. The voltage of B is E_B. The direction of the load current is I_L. The current of B is I_B and, therefore, the current of A is identical to I_B. The position of the regulator is first assumed as at R' and IR and IX are drawn with respect to the current I_A and the voltage of E_B. The voltage required at R' is therefore E_R; the voltage of A is E'_A. The voltage required of the regulator is E'_AE_R and the power-factor of A is cosine φ'. If the regulator is located at R, the line drop triangle is lowered until the point E_R falls on the arc r-r as at E_A which is now the voltage of generator A and which voltage at R is E_D. The regulator must therefore boost the voltage by an amount

equal to E_DE_B and the power-factor of generator A is cosine φ. It should be noted that, for this requirement, the regulator voltage E_DE_B is considerably in excess of the IR voltage drop E_Ba. As a matter of fact, it is as indicated in Fig. 197.

Condition 3

Assuming the same requirements as in Condition 1 except that the power-factor of the load taken from the bus D is to be cosine θ.

The diagram is given in Fig. 200 and is constructed in the same manner as Fig. 198. It has been assumed that each generator carries an equal current and that the total load current is I_L. I_L must therefore be resolved into two equal components, one of which I_A is in phase with E_A. The current in B is therefore I_B as shown. With 100 per cent power-factor on generator A, the resistance and reactance drops are respectively in phase with and at right angles to I_A as in Fig. 198. With the regulator at R, the voltage required of the regulator is E_DE_B as in Fig. 198. The power-factor of the load on generator B is cosine φ and lower than in Fig. 198.

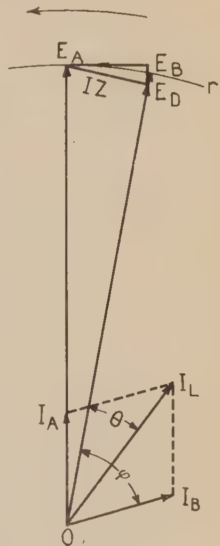


Fig. 200
Vector Diagram Showing Voltage Drop in an Interconnecting Line Due to Varying Power-Factor of Load and Varying Adjustments of the Power-Factor of the Load Carried by the Connected Generators

Condition 4

Assuming the same conditions as in Condition 3 except that generator B operates at 100 per cent power-factor, the diagram is given in Fig. 201 and is constructed in the same manner as Fig. 199. The line drop is drawn

with reference to E_B and I_A. With the regulator at R, the voltage required of the regulator is $E_D E_B$ which voltage requirement, it should be noted, has been materially increased due to the lower power-factor of the load carried by the line and due to the low power-factor of the load on generator A as indicated by the angle φ.

Fig. 201
Vector Diagram Showing Voltage Drop in an Interconnecting Line Due to Varying Power-Factor of Load and Varying Adjustments of the Power-Factor of the Load Carried by the Connected Generators

Condition 5

Assuming any power-factor of load on bus D as cosine θ, and that any current, as may be predetermined, is to be carried by generator A, and at any desired power-factor as cosine φ, find the size of the regulator required and the power-factor of the load on generator B.

In Fig. 202, E_A is the voltage required on bus C, and I_A is the current it is desired to transmit to bus D, the power-factor of the load delivered by generator A being cosine φ as predetermined. The resistance and reactance drops in the line (IR and IX respectively) are drawn with reference to I_A and E_A and give the voltage of generator A at the bus D as E_D. This establishes the direction of the voltage at bus D with respect to generator A. The line current I_L is then drawn and displaced from E_D by the angle θ, the cosine of which is the power-factor of the load taken from bus D. With a load current of I_L and I_A delivered by generator A, generator B must therefore supply the current I_B, its displacement from E_D being

the angle φ', the cosine of which is the power-factor of generator B. As the voltage at bus D is to be equal to E_A, the regulator must boost the voltage at R by an amount equal to $E_D E_B$.

Relation of Line Drop to Regulator Voltage Required

By comparing Fig. 196 with Figs. 198 to 202 inclusive, it will be observed that the line drop (Fig. 197) corresponds to the required regulator voltage only when the regulator is in the position R' and only when the line loss is supplied by the generator which transmits power over the line. With a 100 per cent power-factor load on bus D, with the line constants assumed in Fig. 195, and with 100 per cent current, the line drop is 5.56 per cent. With the generator B operating at 100 per cent power-factor, generator A in Fig. 199 operates at 98.6 per cent power-factor and the regulator voltage required is 5.56 per cent.

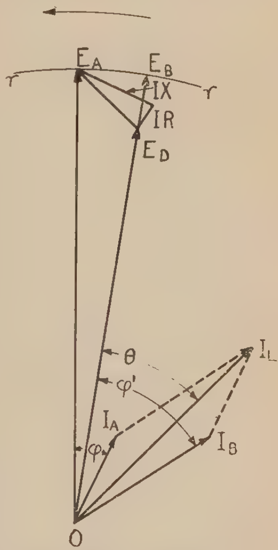


Fig. 202
General Vector Diagrams of Line Drop in an Interconnecting Line

However, with the generator A operating at 100 per cent power-factor (Fig. 198), that is, with B supplying the leading current to compensate for the line reactance, the regulator voltage required is only 1.64 per cent. Similarly, at 80 per cent power-factor load, the line drop is 14.3 per cent. With generator B operating at an 80 per cent or the load power-factor, generator A operates at 72.8 per cent power-factor and the regulator voltage required is 14.3

per cent, whereas with generator A operating at 100 per cent power-factor, the required regulator voltage is, as previously, only 1.64 per cent. That is, the higher the power-factor of the load transmitted over the line, the smaller is the regulator required, the greater is the amount of power which can be carried by the transformers, and the smaller the loss per kilowatt transmitted.

From the foregoing, it is evident that the line drop as determined for a feeder and as given in Fig. 196 determines the size of the regulator required for the interconnection of generating stations, only if the power supplied by each generating station to the common load is delivered at a power-factor as determined by this load. Each generating station may, however, supply power to other and independent lines or feeders, and the power supplied by these feeders may be of any other power-factor. Each generating station may thus be considered as being entirely independent of any other and as supplying a load of any required power-factor, and the tie-in station or bus to which power is supplied may then be considered as an additional load and the transmission line may be considered as a feeder. Under this condition, Figs. 196 and 197 give the line drop and also the voltage requirement of the regulator. For any other condition, the regulator requirements must be determined as illustrated in Figs. 198, 200 and 202.

The diagrams indicate the total voltage adjustment required. As the regulator can, however, lower the voltage, as well as boost it and by an equal amount, the step-up or step-down transformer should have an over or under ratio so that the lowering as well as the boosting of the regulator can be taken advantage of, thereby reducing the size of the regulator by one-half. In case it is desired to

transmit power over an interconnecting line in either direction, it is, however, obvious that with a reversal of the

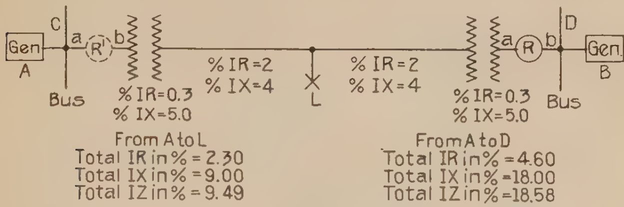


Fig. 203

Diagram Illustrating Voltage Regulation Requirements on an Interconnecting Line Supplying Power at Intermediate Points

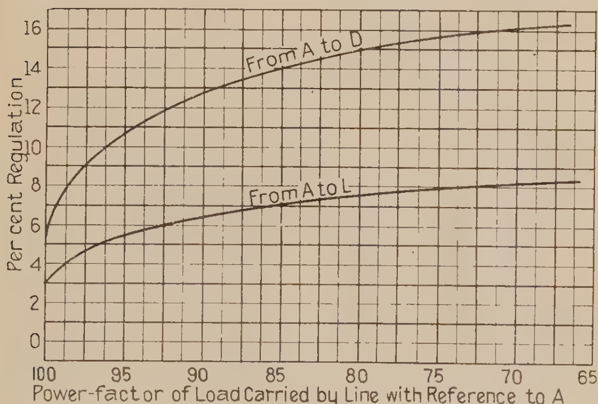


Fig. 204

Curve Illustrating Voltage Regulation Requirements on an Interconnecting Line Supplying Power at Intermediate Points

power transferred, the over ratio of the transformer will also require reversal.

Case II

Assuming an interconnection between two generating stations similar to the one previously considered but with

the interconnecting line supplying power at an intermediate point as at L in Fig. 203, then with this connection, the transmission loss from A to L and from A to D must be

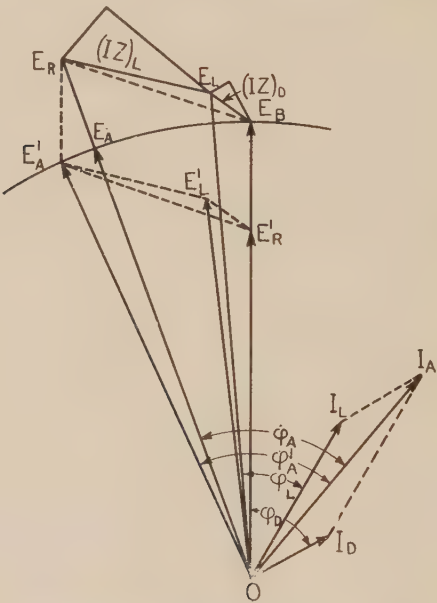


Fig. 205
General Vector Diagram of Voltage Drop in an Interconnecting Line Supplying Power at an Intermediate Point

considered independently with reference to the load and the power-factor of the load at L and D respectively, and as indicated by Fig. 204.

The general diagram given in Fig. 205 is based on the operation of generator A at a power-factor as required by the combined loads at L and bus D, and on the operation of generator B at a power-factor determined only by the load on bus D.

With the regulator at R':

E_B represents the voltage of generator B and of the bus D to which the voltage of generator A must be adjusted by means of the regulator.

I_D = current furnished by generator A to bus D at the power-factor of the load on bus D; that is, cosine φ_D.

$(IZ)_D$ = impedance drop from L to bus D due to the current I_D. The voltage at L must therefore be E_L.

I_L = current load assumed for L and at a power-factor of cosine φ_L.

I_A = the resultant of I_D and I_L; that is, the current carried by the line from A to L.

$(IZ)_L$ = reactance drop from A to L. The voltage required at the b terminal of regulator R' is therefore E_R.

$E_R E_A$ = the voltage required of the regulator.

E_A = the voltage of generator A.

Cosine φ_A = the power-factor of generator A.

If the regulator is installed at R, the voltage of generator A at the a terminal of the regulator R is E'_R so that the regulator is required to boost this voltage by an amount equal to $E'_R E_B$. The voltage at L will be approximately E'_L. As shown, this voltage is subject to a slight correction as it was assumed that the power-factor of the load at L was cosine φ_L. The power-factor of generator A will now be approximately cosine φ'_A. This, however, also requires a slight correction due to adjusting the current I_L for a power-factor at L of cosine φ_L. With the regulator in either location, the voltages on the buses C and D are identical but there is a considerable difference in the voltage at the

load L. This voltage is higher or lower than normal depending on the location of the regulator.

By substituting the constants of the load and the line as heretofore, the size of the regulator can be determined for any condition.

Two Interconnecting Lines Between Generating Stations

If conditions require two interconnecting lines between generating stations, one regulator should preferably be used, as regulator R in Fig. 206. If, however, conditions require a regulator in each interconnecting line, as regulators R_1 and R_2 in Fig. 206, they should preferably be geared or mechanically coupled together so that the phase displacement introduced by the regulators will be identical, under which condition their combined action will be identical to that of a single regulator as at R.

It has been shown that if the voltage of one of two parallel or interconnected generators be varied from the voltage of the other generator, either by changing the field excitation or by means of a regulator, an exchange current will flow through the interconnecting line and through the generators. In like manner it may be shown that, if two regulators, each connected in series with one of two parallel-connected interconnecting lines, as shown in Fig. 206, are not identically adjusted, a circulating current will be established through the two interconnecting lines. This current may flow through the generators in whole or in part or it may circulate through the interconnecting lines only, depending on the individual adjustments of the regulators. The current which flows through the generators due to the regulator voltages is always a wattless current; whereas that circulating through the lines may be a power or a wattless current or a combination of both.

In investigating the results produced by two independently operated regulators respectively in series with two parallel-connected interconnecting lines, it is con-

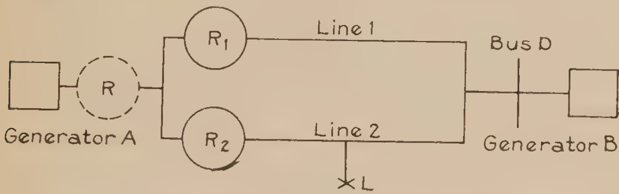


Fig. 206
One-Line Diagram of an Interconnecting Line Consisting of Two Parallel Circuits

venient to consider each line separately. Under no-load conditions the current in each line, due to the secondary voltage of the regulator, is equal to the induced regulator voltage (or that voltage as modified by a phase adjustment of the generators) divided by the impedance of the line, and its direction will be at right angles to and lagging with respect to the secondary voltage of the regulator. This current may therefore have any phase relation to the line or generator voltage depending only on the direction of the secondary voltage of the regulator.

Any voltage change due to either or both regulators will cause a current to flow. If the voltage change is produced by single-phase regulators or by auto-transformers, the regulator voltage will be in phase with the line voltage and a wattless current only will flow, either through the line alone or through both line and generators. If the voltage change is obtained by a polyphase regulator, a phase displacement is also introduced which causes a shift in the generators and may also cause a power current to circulate in the interconnecting lines. However, the power current does not flow through the generators after

they have shifted in phase to compensate for the shift in the phase produced by the polyphase regulators.

Although it is convenient to consider the action of each regulator independently, their combined action determines the value and the direction of the currents in both the generators and in the lines. The results obtained can best be illustrated by vector diagrams. The diagrams given are purposely exaggerated so as to show more clearly the action of the regulators.

The reactance of a line is generally much higher than its ohmic resistance so that the impedance voltage drop of the line is generally approximately in phase with its reactance voltage drop. The direction of the wattless current is at right angles to the reactance voltage; but for the sake of simplicity in the diagrams, the current is shown at right angles to the impedance voltage, that is, at right angles to the regulator voltage.

The diagrams are based on the condition that no load is being transmitted over the interconnecting lines, that the voltages of the generators are identical, and that the resistances and reactances of the interconnecting lines are respectively identical. The impedance voltage drop of each line is assumed as 20 per cent with 100 per cent current flowing, and the secondary voltage of the regulator is assumed to be 10 per cent of the line voltage.

As previously indicated, the regulators can be adjusted so that no circulating current will flow. For the no-load condition, this adjustment is made with both regulators in either neutral position, as illustrated in Figs. 207 and 208. With no regulators in the interconnecting lines, the voltages of generators A and B are equal and in phase as shown in Fig. 208. After the introduction of the regulators, adjusted to their neutral positions at B', the voltages of both

generators are still numerically equal but the voltage of generator A at the terminals of generator B has in effect

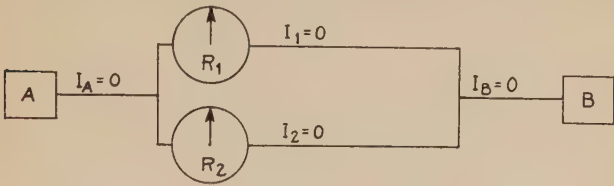


Fig. 207

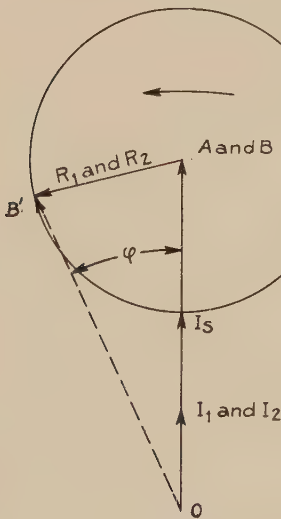


Fig. 208

Figs. 207 and 208

Diagrams of Regulators in Two Parallel Interconnecting Lines with Both Regulators in the Maximum Boosting Position

been shifted to the position OB', that is, the effective voltage of generator A at the terminals of generator B is now OA (the voltage of generator A) plus AB' (the voltage of the regulators).

Due to the voltage of the regulators, the effective voltages of the generators are therefore displaced by the angle φ which displacement causes an exchange current to flow in the same manner as if the generators themselves were displaced through a similar angle. In other words, the voltage of each regulator causes a current to flow in each line as I_1 and I_2 each equal to the secondary voltage of the regulator (assumed as 10 per cent) divided by the impedance of the line (assumed as 20 per cent) or 50 per cent of the full-load line current. This current is lagging with respect to the regulator voltages producing them but is in phase with the generator voltage. These currents are in phase and equal in value, and their sum is I_s. I_s, therefore, represents the power current supplied by generator A to generator B.

As the generators are free to adjust themselves, generator B will advance and generator A will lag until the voltage due to their phase displacement is equal but opposite to the voltage of the regulators. Assuming, for convenience, that the entire shift in the generators is produced by generator B, then generator B will shift to position OB' in Fig. 208. With generator B in this position, its armature will be displaced from that of generator A by the angle φ and the voltage at its terminals will be ahead of the voltage at the terminals of generator A by the angle φ corresponding to the voltage $B'A$. This voltage is equal and opposite to the regulator voltage AB' under which condition the effective voltages of both generators are equal and in the same direction, that is, identical. After this adjustment of the generators, no current will therefore flow through the generators. No circulating current will flow through the lines for the reason that, with respect to the lines, the regulator voltages are equal and opposite.

The final current conditions are shown in Fig. 207. It should be noted that, in the case illustrated, the two regulators are equivalent to a single regulator in series with a single interconnecting line.

Figs. 209 and 210 illustrate conditions with both regulators in the maximum boosting position. Each regulator causes a current to flow in each line. The current in each line is, however, lagging behind the generator voltage by 90 degrees and is, therefore, wattless. The currents are equal and in phase and each has a value of 50 per cent of the full-load line current. Generator *A* therefore supplies 100 per cent full-load current to generator *B*. However, as the current in this case is wattless, no shifting in the phase position of either generator occurs. This condition is also identical to one in which a single regulator is used in a single interconnecting line.

Figs. 211 and 212 illustrate conditions with one regulator in its maximum boosting and the other in its maximum lowering position. As previously stated, the voltage of each regulator produces a current practically at right angles to the regulator voltage and lagging with respect to this voltage. The current in each line is equal to 50 per cent of the full-load current. The voltages of the regulators are opposed in direction with respect to the line voltage. Hence, the currents in the two lines also flow in opposite directions with respect to the line voltage but in series with respect to the lines themselves, as shown in Fig. 211. Under this condition, a circulating current exists in the lines, but not in the generator.

In Figs. 213 and 214, one regulator is in one neutral position whereas the other regulator is in the opposite neutral position. As in the previous case, the currents induced in the two lines flow in opposite directions with

reference to the line voltage but are in phase and in series with each other with reference to the two lines themselves.

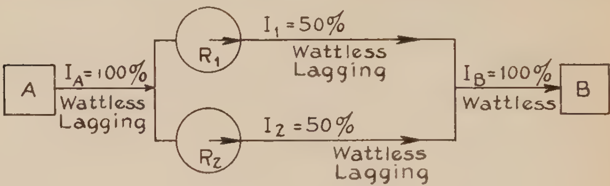


Fig. 209

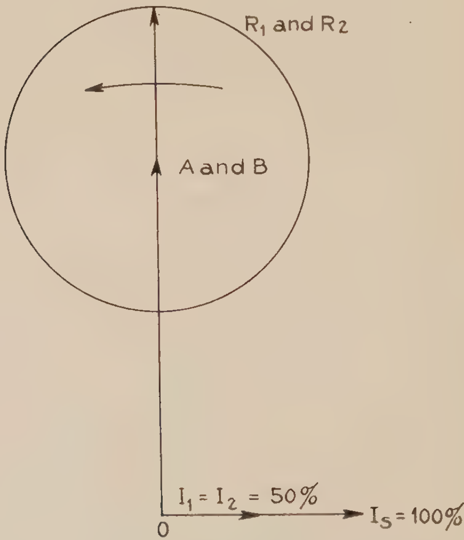


Fig. 210

Figs. 209 and 210
Diagrams of Regulators in Two Parallel Interconnecting Lines with Both Regulators in the Same Neutral Positions

The currents now, however, represent power currents as they are in phase with the line voltage. However, as the

phase displacement introduced by one regulator is equal and opposite to the phase displacement introduced by the

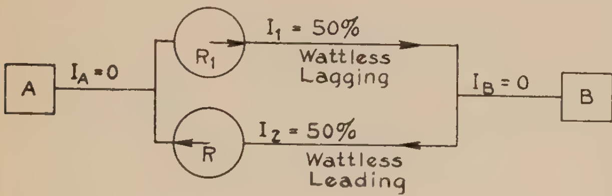


Fig. 211

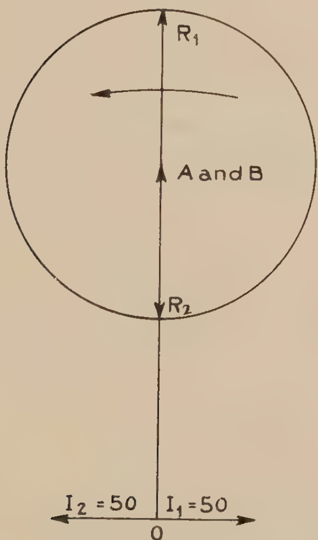


Fig. 212

Figs. 211 and 212
Diagrams of Regulators in Two Parallel Interconnecting Lines with the Regulators in Opposite Neutral Positions

other regulator, the current circulates in the line only and does not cause a phase displacement of the generators.

Were power being transmitted over the lines, the current due to the regulator voltages would combine with the

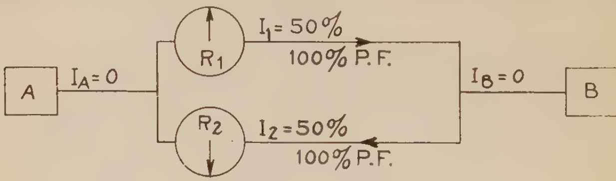


Fig. 213

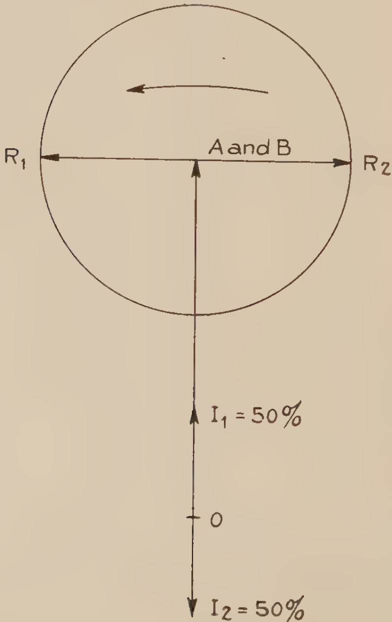


Fig. 214

Figs. 213 and 214

Diagrams of Regulators in Two Parallel Interconnecting Lines with One Regulator in Its Maximum Boosting and the Other in Its Maximum Lowering Position

load currents with the result that the lines would transmit unequal amounts of power.

In Figs. 215 and 216, both regulators are half way between their maximum boosting and neutral positions but

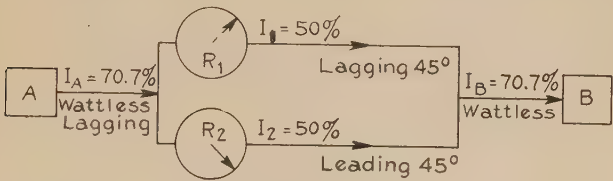


Fig. 215

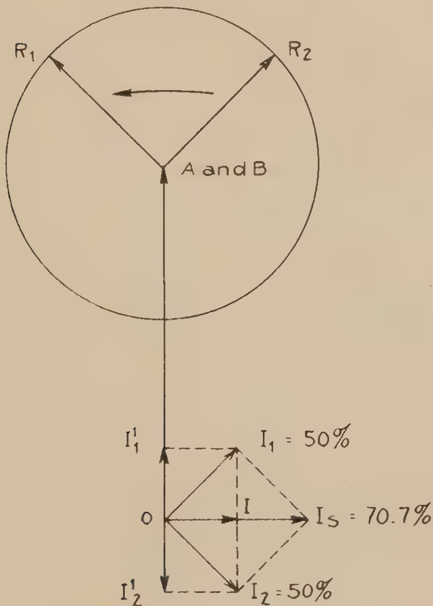


Fig. 216

Figs. 215 and 216

Diagrams of Regulators in Two Parallel Interconnecting Lines with Both Regulators Displaced by 45 Degrees from the Same Neutral Position

are displaced from each other by an angle of 90 degrees. Each regulator produces a current in the line with which

it is in series, and lagging behind the regulator voltage by 90 degrees, as I_1 and I_2 in Fig. 216. Each of these currents may be resolved into components respectively in phase with and at right angles to the line voltage, as: I'_1 and I; and I'_2 and I. The power components I'_1 and I'_2 are equal and opposite as in the previous case. They therefore circulate only in the line and do not cause a displacement of the generators The wattless components of the currents are, however, in phase and their sum I_s (equal to 70.7 per cent of full-load current) lags with respect to the line voltage and circulates through the generators. The current in each line is therefore 50 per cent. In line *1* it is lagging; whereas in line *2* it is leading, with respect to the line voltage, by an angle of 45 degrees and as indicated in Fig. 215.

In Figs. 217 and 218, regulator R_1 is half way between its maximum boosting and a neutral position, whereas regulator R_2 is half way between its maximum lowering and a neutral position corresponding with the neutral position of regulator R_1. Before the generators shift in phase so as to compensate for the phase displacement introduced by the regulators, the currents in the lines are respectively I_1 and I_2 each equal to 50 per cent. These currents resolved into their components in phase with and at right angles to the line voltage are: I and I'_1; and I and I'_2. The I components of these currents are power currents and are equal and in the same direction, their sum being I_s. The wattless components, I'_1 and I'_2 also are equal but opposite in direction. The power current I_s flows through the generators and causes a shift in phase which phase shift of the armatures must be equal to the phase displacement introduced by the regulators but opposite thereto in direction.

As in this case, the regulator voltages are symmetrical with respect to the neutral positions of the regulators, the

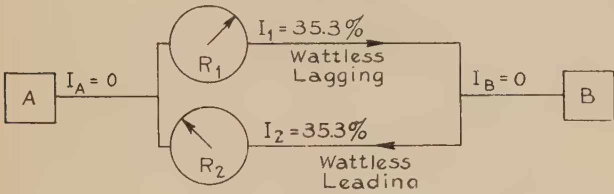


Fig. 217

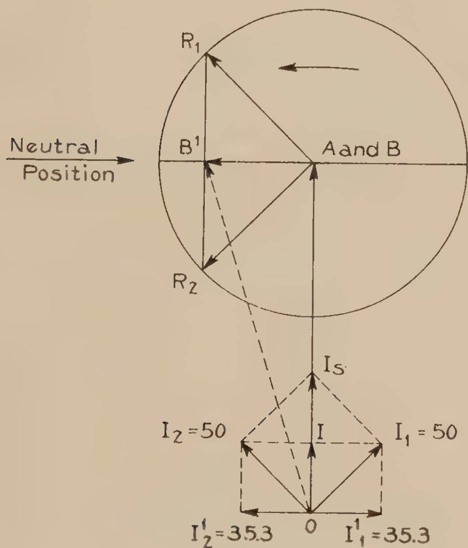


Fig. 218

Figs. 217 and 218

Diagrams of Regulators in Two Parallel Interconnecting Lines with Both Regulators Displaced by 45 Degrees from the Maximum Boosting Position

phase displacement introduced by both regulators is AB' in Fig. 218. Generator B is therefore advanced in phase to

position OB' so that the vector sum of the voltage of generator A (that is, OA) and the component of the regulator voltage AB' which causes the power current to flow, is equal to and in phase with the voltage of generator B which is now OB'; that is, generator B will move to the position of OB', as illustrated in Figs. 207 and 208. After generator B has assumed this position, the current I_s becomes zero. The components of the regulator voltages in phase with the line voltage, that is, $B'R_1$ and $B'R_2$, are, however, still effective and cause a wattless current to flow through the lines. These currents are equal and, with reference to the line voltage, are opposite in direction, as illustrated in Figs. 211 and 212. With reference to the lines themselves, they are therefore in series and, hence, circulate in the lines only. The value of this current is equal to the component of the regulator voltage in phase with the line voltage divided by the impedance of the line. With the constants assumed. the numerical value of this circulating current is 35.3 per cent of full-load current.

Figs. 219 and 220 show regulator R_1 in a neutral position and regulator R_2 in its maximum lowering position. Before the generators have shifted in phase to compensate for the phase displacement introduced by the regulators, the current due to regulator R_1 is I_1 and equal to 50 per cent of full-load current, and the current due to regulator R_2 is I_2 and is also equal to 50 per cent of full-load current. The former is a power current and the latter is a wattless current.

As the power current is due to only one of the regulators and no compensating power current is produced by the other regulator, it must flow through the generators and thus cause a sufficient shift in the phase of the generators to reduce the power current flowing through the generators

to zero. Were generator B shifted in phase to B' (Fig. 221) so that its voltage phase displacement were equal to that

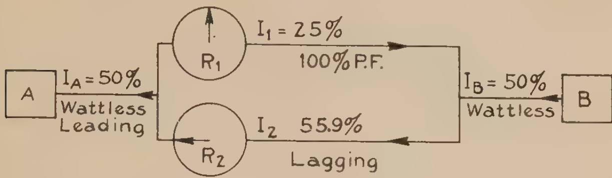


Fig. 219

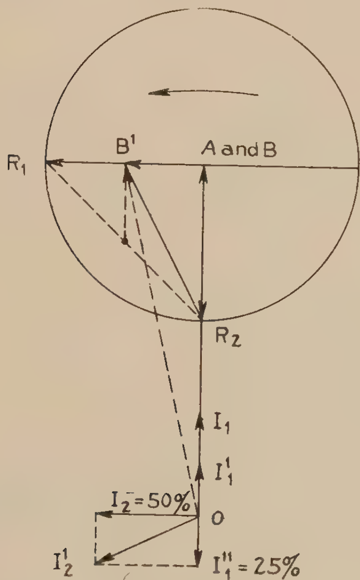


Fig. 220

Figs. 219 and 220

Diagrams of Regulators in Two Parallel Interconnecting Lines with One Regulator in Its Maximum Boosting and the Other in a Neutral Position

introduced by the regulator, the current in line *1* would be reduced to zero as illustrated in Figs. 207 and 208. However,

with reference to line *2*, this shift in the phase position of generator B would produce a voltage difference between generators A and B equal to $B'A$ which voltage would cause a power current I_A to flow in line *2* equal but opposite in direction to I_1 in Fig. 220. As the current in line *1* is zero, this power current would flow from generator B to generator A and cause a shift in the phase relations of the generators. In order to reduce the power current in the generators to a zero value, it is therefore obvious that generator B must shift to a position in which the power current in line *1* (and due to regulator R_1) is equal but opposite in direction to the power current in line *2* due to the phase displacement between the generators. In Fig. 220, this position of generator B is OB' in which the phase displacement of generator B produces a voltage $B'A$, equal but opposite to one-half of the voltage due to regulator R_1. Under this condition, one-half of the voltage of regulator R_1 is still effective in producing a power current in line *1* as I'_1 and equal to 25 per cent. The displacement of generator B causes a current of equal value but opposite direction, as

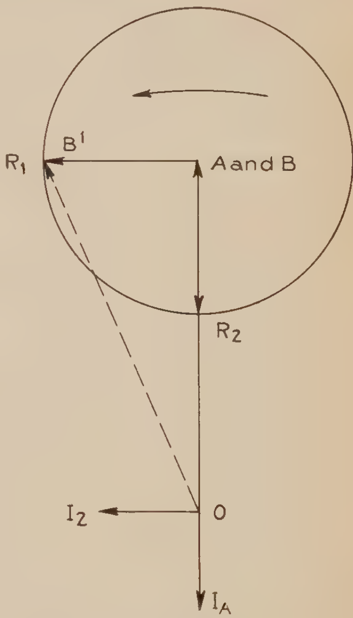


Fig. 221
Vector Diagram of Circulating Current Due to Phase Shift of Regulator Voltage or Due to the Angular Displacement of One Generator

I''_1, to flow in line *2*. Regulator R_2 also causes a wattless current equal to 50 per cent to flow in line *2*. The total current in line *1* is therefore 25 per cent. This is a power current. The total current in line *2* is 55.9 per cent. This current consists of 25 per cent power current and 50 per cent wattless current. The power currents in the two lines are now equal and in opposite directions, and therefore circulate in the lines only. The wattless current in line *2* flows through the generators for the reason that regulator R_1 produces no corresponding and opposite wattless current in line *1*. The current I'_2 flowing in line *2* is practically at right angles to and lagging behind the resultant of the regulator voltage R_2 and the voltage due to the phase displacement of generator B which is AB'. In other words, I'_2 is the current due to the resultant voltage R_2B'.

For any other positions of the regulators, the flow of current in the lines and in the generators due to the regulator voltage may be determined in a similar manner. If, in Fig. 222, the positions of the regulators represent any positions whatsoever, and if the impedances of the lines are unequal and their resistances and reactances not proportional, then, before the generators are adjusted to compensate for the phase displacement introduced by the regulators, the current in each line will be equal to the secondary voltage of the regulator in series with that line divided by the impedance of that line. These current values for line *1* and line *2* are I_1 and I_2 respectively, and they are respectively at right angles to the reactance voltage drops in the lines. Each of these currents may be resolved into components in phase with and at right angles to the line voltage. The components for I_1 are a_1 and b_1 respectively, and for I_2 they are a_2 and b_2 respectively. The algebraic sum of a_1 and a_2 is I_s. This is a power current and causes a

phase displacement of the generators as shown in Figs. 208 and 220. The generators will shift in phase either

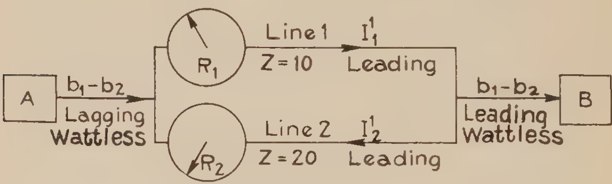


Fig. 222

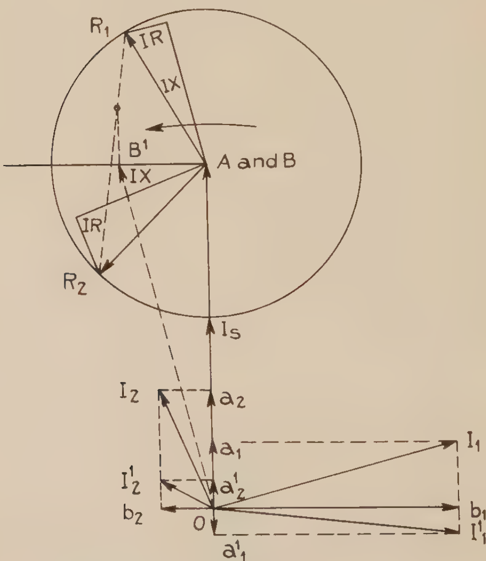


Fig. 223

Figs. 222 and 223
General Diagrams of Regulators in Two Parallel Interconnecting Lines

until this current becomes zero or until the difference in value between the power currents due to the two regulators

is equally divided in the two lines but flowing in opposite directions. The difference in the value of these currents as shown, is $a_2 - a_1$. Each of the vectors a'_2 and a'_1 is, therefore, drawn equal to one-half of $a_2 - a_1$ but they are drawn in opposite directions and represent the power currents flowing in line *2* and line *1* respectively after generator B has shifted to some position as OB'.

The combinations of the wattless components b_1 and b_2, with the power components a'_1 and a'_2, respectively, are represented by I'_1 and I'_2 which now represent the currents flowing in lines *1* and *2*. The current flowing in the generators is equal to $b_1 - b_2$ and is wattless.

The values of the various currents for any condition are determined by the secondary voltage of the regulators as modified by the phase adjustment of the generators and by the impedances of the lines, and their angular position to the line voltage, that is, their power-factor, is modified by the relation of the resistances of the lines to their reactances.

The preceding considerations have been based on no load being carried by the line. However, it is obvious that, under load conditions, the regulator displacements which have been considered and the current flow resulting therefrom would be modified by the load current and by the line drop due to the load current. The voltage component of the regulator which causes the wattless current is in phase with and opposite to the ohmic voltage drop in the line due to the energy component of the load current flowing in the line. If the regulators are adjusted so that the voltage change due to the regulators is just equal and opposite to the total voltage drop due to the load, no wattless current will flow due to the regulator voltages. Any excess or deficiency in the regulator voltage will,

however, cause a wattless current to flow in one direction or the other through the lines and generators. An unequal adjustment of the regulators will likewise cause a wattless current to flow through the lines and generators, and a power current to flow through the lines.

The currents due to any resultant unbalanced voltage or due to any phase displacements of the regulators combine with the load currents in the generators and in the lines, and their vector sums give the value and the direction of the actual currents flowing. The reactive voltage drop in the lines due to the load current causes a phase displacement of the voltages which is compensated for by a phase shift of the generators whereas the resistance drop causes the flow of a wattless current.

The primary object of the regulators is the voltage adjustment of the line so as to control the power-factor of the various generators. The illustrations indicate the results obtainable by displacing the regulators. As shown, both the load and power-factor of the load carried by each line may be varied by displacing the regulators. In case a load is supplied from one of the lines at some point between their common connections, as, for instance, at point L, Fig. 206, such a displacement of the regulators may be advantageously used. In the application of this arrangement, it is suggested that initially both regulators be identically adjusted so as to adjust the power-factor of the generators, after which one or both of the regulators may be adjusted so as to obtain the proper division of power in the transmission lines.

In this connection, it is interesting to note the action of a regulator in a loop system as illustrated in Fig. 224. By the use of a regulator, the voltage of which is always in phase with the line voltage (as, for instance, the single-phase

induction regulator or the step-by-step compensator type), the voltage of one side of the loop may be increased so as to divide the current flowing in the two legs of the loop as may be desired; that is, so that no current flows at some point as at *A*. If, however, a polyphase regulator is so used, a circulating current will flow, due to the phase displacement introduced by the regulator. This current, as shown, depends in value and in direction on the voltage of the regulator, on the ohmic resistance and the reactance of the line, on the line voltage drop due to the load, and on the phase displacement of the regulator.

The Automatic Control of Regulators Used in Interconnected Systems

The voltage of an interconnecting line can be automatically regulated by means of a regulator in the station containing the generator which furnishes the power transmitted over the line, and also by means of a regulator in the receiving station.

If the transmission line is considered as a feeder only, the line drop compensator can be adjusted so that the regulator will compensate for the line drop to any given or predetermined point on the feeder even to the station where parallel connection is made with other generators.

It might seem that, if the regulator is installed at the end of an interconnecting line (that is, in the receiving station), advantage could be taken of the line drop to this point and that no line drop compensator would be required for the reason that the contact-making voltmeter (and, hence, the regulator) operates due to a change or drop in voltage from normal. The voltage at this point is, however, controlled by the generator there connected, and as

previously shown, no voltage difference exists between the end of an interconnecting line and the generator at that point. It is therefore necessary to make use of a line drop compensator; but because of the reversal of the current

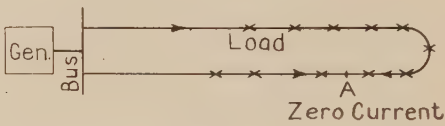


Fig. 224
Division of Current in a Loop System

(that is, it is incoming instead of outgoing), it is necessary to reverse the connection of the current transformer, so that its voltage is opposed to that of the potential transformer which supplies the contact-making voltmeter. The voltage of an interconnecting line can thus be as satisfactorily controlled as the voltage of a feeder.

Regulators used in interconnecting lines are, however, usually required for power-factor control rather than for voltage control.

No satisfactory contact-making power-factor indicator has, however, yet been developed, and regulators can therefore not be automatically operated in this manner except under certain limitations. Fig. 225 gives a diagrammatic representation of a power-factor indicator for a three-phase system. It consists primarily of a series coil and a shunt coil connected as shown and arranged so that the coils are relatively adjustable to each other with regard to their angular positions. The current coil is connected in series with one phase, and the shunt coil across the other two phases.

With the current in the series coil at right angles to the current in the shunt coil, there is no torque between the

coils; but, when the current is at any other angle a torque is produced and causes the movable coil to rotate into the no-torque position, that is, the moving coil indicates the phase displacement.

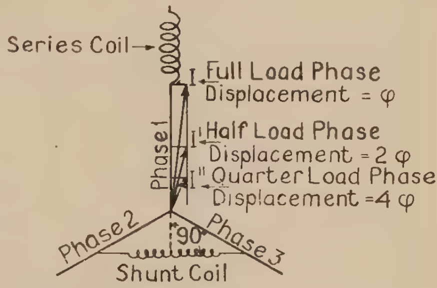


Fig. 225

Power-Factor Indicator Used as a Contact-Making Voltmeter to Control a Polyphase Regulator in an Interconnecting Line

Contacts may be mounted on the pointer of the moving element, as in a contact-making voltmeter. An appreciable torque is required to make a sufficient contact to operate the relay switch for the operating motor of a regulator. This torque necessarily depends on the amount of current in the series winding and its phase displacement with reference to the current in the shunt coil.

Assuming that the horizontal component of 100 per cent current displaced by an angle φ is just sufficient to operate the meter, then at 50 per cent current, the displacement required will be twice as great, and at 25 per cent current, four times as great, etc. That is, if the meter can be adjusted so that it will hold the power-factor desired within 1 per cent with 100 per cent load current, it will not be able to hold the power-factor so close at lower loads, the accuracy of regulation decreasing with the load.

The power-factor meter arranged as a contact device is therefore not satisfactory unless the load current is approximately constant. A standard power-factor indicator may, however, be used if the regulator is adjusted by means of a hand-operated switch.

In order to determine the adjustment of the regulator, a standard power-factor indicator should be connected between the generator (the power-factor of the load of which it is desired to control) and the regulator. The indication of the instrument will then show the power-factor at which the generator is supplying power to the interconnected system which power-factor can be adjusted in any manner desirable within the limits of the voltage range of the regulator.

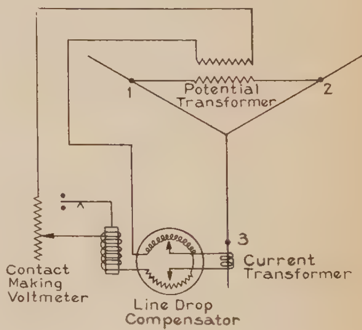


Fig. 226

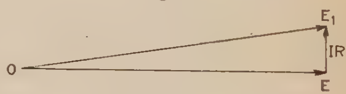


Fig. 227

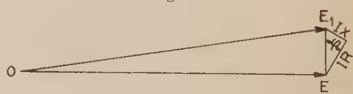


Fig. 228

Figs. 226 to 228

Use of Contact-Making Voltmeter to Control a Polyphase Regulator in an Interconnecting Line

A modification of the preceding arrangement, making use of a standard contact-making voltmeter and a line drop compensator, has been used. The connections are shown in Fig. 226 and the vector diagrams in Figs. 227 and 228. The line drop compensator is connected in series with one phase of a three-phase system through a current transformer and the contact-making voltmeter is connected across the other two phases but in series with the line drop compensator as shown.

With this arrangement, the contact-making voltmeter is adjusted for the voltage across the generator. With the required power-factor on the line and with full-load current

flowing, the voltage across the line drop compensator is adjusted so as to be at right angles to that across the contact-making voltmeter, that is, in phase with the voltage of the line in which the compensator is connected. In Figs. 227 and 228, OE is the voltage across phases 1 and 2 of the generator, and EE_1 is the voltage across the line drop compensator. OE_1 is the voltage across the contact-making voltmeter. EE_1 varies in value with the load, and in direction, with the power-factor of the load.

With this arrangement, it is not desired that the regulator operate due to a change in the load but only due to a change in the power-factor of the load. The line drop compensator adjustment must therefore be such that a load variation of from zero to its maximum, which produces a corresponding voltage drop in the compensator, will not cause the contact-making voltmeter to operate. In other words, EE_1 must be limited in value so that the change in the voltage across the contact-making voltmeter of from OE (representing zero load) to OE_1 (representing the maximum load) will not cause it to operate the regulator. The voltage EE_1 may be of any value within the limit given, but the greater its value, the more accurate will be the adjustment of the regulator for the control of the power-factor. With this voltage equal to 15 per cent of OE, the total variation in the voltage across the contact-making voltmeter is only 1 per cent which is not sufficient to cause the regulator to operate provided the contact-making voltmeter is adjusted for the average voltage.

A change in the power-factor of the load causes a corresponding shift in the angular position of the voltage EE_1, that is, E_1 rotates to the right or left. The voltage due to this phase shift or displacement is practically in phase with the voltage across the contact-making volt-

meter and it is therefore added to or deducted from it depending upon whether the current causing this voltage drop is leading or lagging. This increase or decrease in the voltage across the contact-making voltmeter causes it to operate the regulator which in turn readjusts the line voltage so that the desired power-factor is again obtained.

The compensator may be adjusted so that the regulator will maintain any power-factor of load. If it should be desired to maintain a 100 per cent power-factor load on the line at the point where the regulator is installed, the reactance element of the line drop compensator is cut out by means of the dial switch. With this adjustment EE_1 will be at right angles to OE, only when the load in the feeder has a power-factor of 100 per cent. Any deviation from this power-factor causes the regulator to act and to readjust it.

Should a power-factor of cos φ (Fig. 228) be desired, it is necessary only to adjust the reactance of the compensator so that the voltage drop in the resistance element is displaced from the total voltage across the compensator by the angle the cosine of which represents the power-factor of the load it is desired to maintain. With this adjustment of the compensator, the conditions are identical to those shown in Fig. 227 and the regulator will be adjusted according to the deviations of the total voltage across the compensator from its 90 degree relation to the voltage across phases 1 and 2 of the line.

The operation of the regulator depends on the value of the wattless component of the load current and is independent of the power component of this current. The wattless current may therefore have the same value at no load or at full load. Hence, this method, as the

preceding one, constitutes a power-factor control only with full load or approximately full load on the feeder controlled.

However, the arrangement will limit the wattless component to any desired value regardless of the load. The arrangement outlined makes use of standard control apparatus and, as stated, has been used with satisfactory results.

The standard connections of the contact-making voltmeter with its line drop compensator can, however, also be used for the control of the power-factor as well as for voltage control. By adjusting the line drop compensator for the line resistance and reactance drops, the generator furnishing the power transmitted over the line operates at the power-factor of the load as modified by the resistance and the reactance of the line, and as illustrated in Fig. 199. If the load has a power-factor lower than 100 per cent, as shown in Fig. 201, this adjustment still applies.

Any power-factor of load supplied by a generator to an interconnected system may be maintained by adjusting the resistance and the reactance of the compensator for other values than those corresponding to the line. For instance, if generator A (in Fig. 198) is to furnish power at 100 per cent power-factor, the compensator is adjusted for a voltage drop lower than that corresponding to the line drop, that is, for a value equal to $E_D E_B$ in Fig. 198.

By thus varying the adjustment of the compensator, a control of the power-factor is obtained, the accuracy of which control is independent of the amount of current flowing. However, this method also has its limitations in that it is inaccurate if power is taken from the interconnecting line at intermediate points.

If power is transferred from either bus to the other and with a regulator in series with the transmission line, it should be noted that, as the direction of the current in the line is reversed, the direction of the boost and the lower of the regulator reverses also. That is, a right-handed rotation of the regulator will boost the voltage with one direction of power transfer, but will lower the voltage if the direction of the power transfer is reversed. The total range of the regulator, however, is not changed, and it only will be necessary for the operator to know the direction of the transfer of power to determine the proper adjustment of the regulator.

The Advantage of Power-Factor Control

As has already been stated, the output of electric generating and transforming apparatus is limited by the heating of the windings, and the lower the power-factor the less will be the amount of power which can be handled for the same heating. For the same heating, the power which can be handled by the generators and transformers varies directly as the power-factor. That is, at 90 per cent power-factor, 90 per cent of the maximum power can be handled. At 50 per cent power-factor, only one-half of the power for which the apparatus is designed can be handled. From this, it is evident that, in the interconnection of systems, it is highly desirable to control the power-factor of the load of the various generators and that carried by the transformers and the transmission line in order to obtain the maximum output at the lowest initial and operating costs.

The induction regulator is an ideal device for the voltage adjustment of interconnected systems for the control of the power-factor. There are no continuously

rotating parts and no making and breaking of current. The regulator has a high efficiency, and because of its uniform voltage regulation, as close an adjustment of the power-factor can be obtained as desired. The induction regulator is being used to a considerable extent for this purpose, and from present indications, it will be used much more extensively in the future.

SECTION XXIV

SELECTION OF REGULATOR

The kv-a. rating of the induction regulator is based on its transformer capacity at full load and not on its range of control. A regulator for a 100 kv-a. circuit having a boost and lower of 10 per cent is rated 10 kv-a. The regulator is designed to produce the specified range in voltage with the feeder delivering full load kv-a. at about 85 per cent power-factor. The no-load ratio is therefore greater than indicated by the rating and is about 9 to 1, that is, the regulator will produce a boost and lower of about 11 per cent or a total change in the voltage of the circuit controlled of 22 per cent at no load and 20 per cent at full load.

In order to take full advantage of the regulator capacity, the bus voltage should exceed the voltage required at the center of distribution, by the amount of the line drop at half load. At half load, the regulator will then be in the neutral position, and the over voltage of the bus will be just sufficient to compensate for the line drop at one-half load, giving normal voltage at the center of distribution.

At no load, the regulator will lower the voltage, as supplied by the bus on the regulated side of the feeder, so as to give normal voltage at the center of distribution, and at full load it will boost the voltage of the bus and again supply normal voltage at the center of distribution.

The regulators generally used for both lighting and power circuits have a range of 10 per cent boost and 10 per cent lower. Single-phase regulators are always used to control single-phase circuits, but either single-phase or polyphase regulators may be used to control polyphase circuits.

Three 10 per cent single-phase regulators used to control a three-phase system will give a 30 per cent voltage range if the regulators are wound for the voltage between phases, but will give a 20 per cent range if they are wound

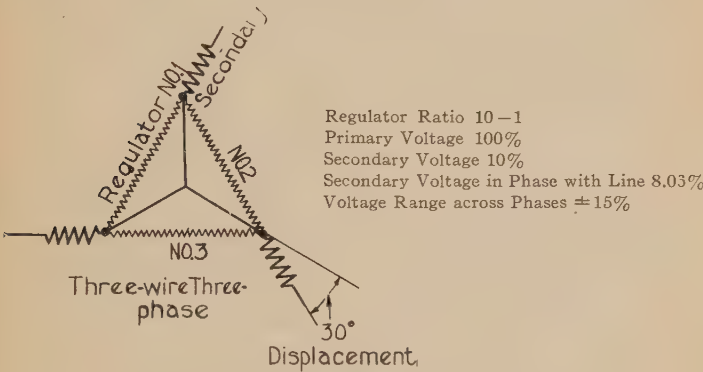


Fig. 229
Connections of Three Single-Phase Regulators in a Three-Phase Three-Wire Feeder

for the Y voltage of the circuit. This is illustrated in Figs 229 and 230.

In the former case, the regulator voltage is out of phase with the line voltage by 30 degrees. The regulator voltage is therefore only 85 per cent effective and the total voltage range across the feeder is ± (the secondary voltage of the regulator times 0.86 times 1.73).

If a total of ± 10 per cent voltage regulation of the feeder is required, it is therefore preferable to use three standard 7.5 per cent regulators. These will produce a range of ± 11.2 per cent voltage variation between phases.

In obtaining the excitation of the regulator from between the neutral and the line, the regulator voltage is in phase as shown in Fig. 230. The excitation voltage of the

regulator is the Y voltage, and a 10 per cent regulator will therefore produce a 20 per cent voltage range in the feeder, between the neutral and the phase line. In making this comparison, it should be borne in mind that a regulator

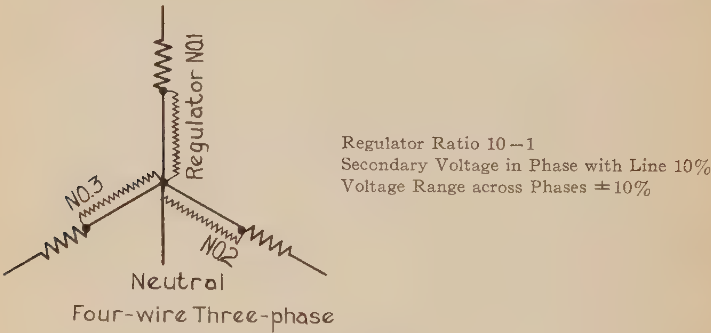


Fig. 230
Connections of Three Single-Phase Regulators in a Three-Phase Four-Wire Feeder

excited across the line is wound for a voltage 1.73 times the voltage from the line to the neutral or phase voltage. The former regulator is therefore proportionally larger in kv-a. capacity than the latter, and consequently produces a greater voltage range.

In designing three-phase regulators, this feature is taken care of in the design itself. The primary winding of each phase is wound for the phase voltage which is 58 per cent of the voltage between phases, so that by the combined action of the phase windings of the secondary, a resultant boost or lower of 10 per cent is obtained on a three-phase feeder.

Combination of Regulator and Boosting Transformer

Conditions sometimes occur in which it is not feasible to operate the station bus at a voltage which is the average

of the no-load and full-load voltage required at the station end of the feeder. For such cases, it is usually economical to use an auto-transformer and a regulator. If, for instance, a feeder should require a range of voltage control from the normal bus voltage to 120 per cent bus voltage, it is more economical to install an auto-transformer which will permanently boost the voltage of the feeder by 10 per cent and a regulator having a boost and lower of 10 per cent than to install a regulator having a boost of 20 per cent. The latter regulator would also have a lowering capacity of 20 per cent, which range would be of no value, and this regulator would have twice the kv-a. capacity of the one required with the auto-transformer.

Single-Phase and Polyphase Regulators

The choice between single-phase and polyphase regulators depends on the requirements. For the control of single-phase circuits, there is no choice; but for the control of polyphase feeders, either single-phase or polyphase regulators may be used. The polyphase regulator will produce the same voltage change in each of the phases regardless of whether the bus or feeder voltage or the load on the feeder is balanced or unbalanced. If this design of regulator is automatically controlled, the voltages of all phases will therefore necessarily be adjusted in accordance with the voltage requirement of the phase across which the contact-making voltmeter is connected. By the use of two interconnected current transformers, the voltage adjustment may be modified to some extent so that an average compensation for an unbalanced load can be obtained. However, by using single-phase regulators, the load voltage of each phase can be maintained constant regardless of whether the supply voltage is balanced or whether the load

is unbalanced, provided, however, that the total voltage range does not exceed the kv-a. capacity of the regulators.

Voltage Regulation of Single-Phase Circuits

As already stated, the control of the voltage of a single-phase feeder requires a single-phase regulator. There is no

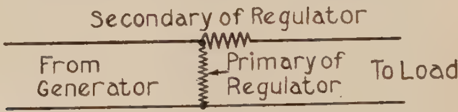
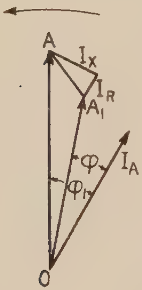


Fig. 231
Connections of a Single-Phase Regulator in a Single-Phase Line

choice in the arrangement; the choice exists only in the voltage range. The diagram of connections is given in Fig. 231 and the vector diagram in Fig. 232. In Fig. 232,



OA = Generator Voltage
OA_1 = Load Voltage
I_A = Line Current
I_R = Ohmic Line Drop
I_x = Reactive Line Drop
Cos φ Power-Factor at Load
Cos φ_1 Power-Factor at Generator
AA_1 = Line Impedance
$OA = OA_1$ Effective Line Drop

Fig. 232
Vector Diagram of Voltage Drop in a Single-Phase Line

the voltage at the station bus is OA; the current in the feeder is I_A; the power-factor of the load is cos φ; the voltage drop in the feeder is AA_1. The voltage range required of the regulator is therefore $OA - OA_1$. The

power-factor of the load at the bus is cos φ_1 which is less than the power-factor of the load due to the impedance voltage drop AA_1 of the line.

Voltage Regulation of Three-Phase Feeders

A three-phase feeder carrying a balanced load can be regulated and correct results obtained by any one of the following arrangements:

One three-phase regulator,
Two single-phase regulators,
Three single-phase regulators.

The arrangements are shown diagrammatically in Figs. 233, 234, and 235, respectively. It should be noted that if, with each arrangement, the regulator secondary voltages are respectively equal, the feeder voltages are equal also.

If the load is unbalanced, the regulation of all three phases will be correct only where three single-phase regulators are used.

Because of the difference in both initial and operating costs of the three methods of regulation, it is important to predetermine the regulation obtainable by each method. This regulation depends on the following factors:

Line resistance and line reactance,
Unbalancing of current,
Power-factor of load,
Phase rotation,
What phase or phases are to be regulated.

Because of the large number of factors involved, the solution of the problem is somewhat complex. The general method of determining the voltages of the unregulated feeder will therefore be given and applied to a feeder some of the constants of which are known.

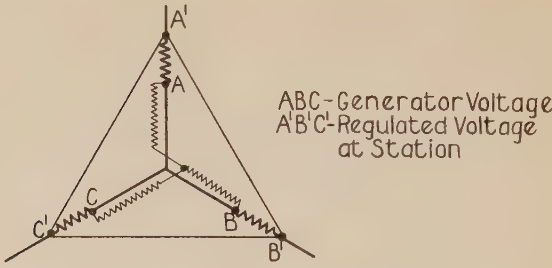


Fig. 233
Connections of Three-Phase Regulator in a Three-Phase Line

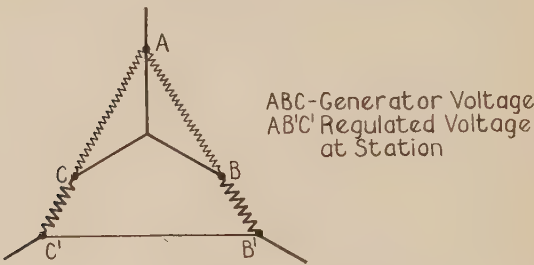


Fig. 234
Connections of Two Single-Phase Regulators in a Three-Phase Line

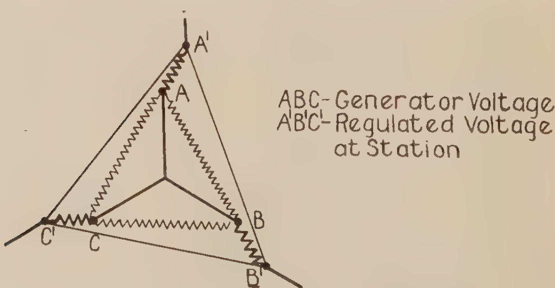


Fig. 235
Connections of Three Single-Phase Regulators in a Three-Phase Line

A vector diagram of a three-phase unbalanced feeder is shown in Fig. 236. The line drop is the difference between the balanced generator voltage ABC and the load voltage $A_1B_1C_1$.

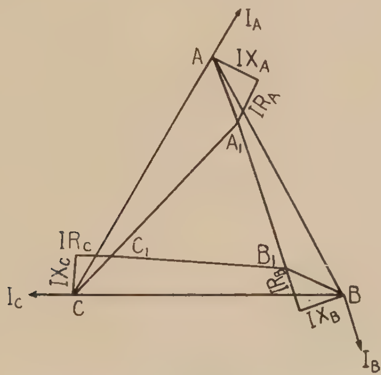


Fig. 236
Vector Diagrams of the Voltage Drop in a Three-Phase Line Due to an Unbalanced Load and the Voltage Regulation Requirements

On the assumption that the voltage at the load is to be equal to the voltage at the bus, the voltages at the station end of the feeder which satisfy the load conditions illustrated in Fig. 236, are indicated in Fig. 237. The bus voltage is ABC, and the voltage drops in the three lines are AA_1, BB_1 and CC_1, respectively. AA' in Fig. 237 is equal to AA_1 in Fig. 236, etc. Hence the required voltage on the feeder at the station is $A'B'C'$. The regulation obtainable by the use of a three-phase regulator; two single-phase, and three single-phase regulators is illustrated in Figs. 238, 239 and 240, respectively.

By using a three-phase regulator, the voltages of all three phases are varied by an equal amount as indicated

in Fig. 238 and it is therefore impossible to satisfy the voltage requirements of all three phases unless they are balanced. The generator voltage is *ABC*, an equilateral triangle. The regulated voltage is *A′B′C′*, also an equi-

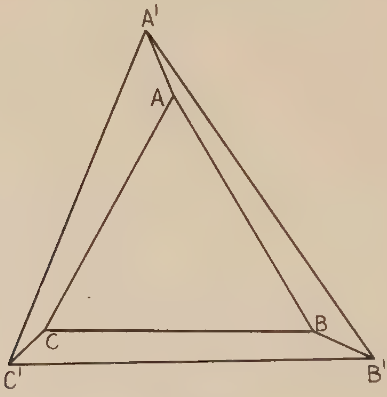


Fig. 237
Vector Diagram of the Voltage Drop in a Three-Phase Line Due to an Unbalanced Load and the Voltage Regulation Requirements

lateral triangle; whereas the requirements demand an unequal triangle, as *A′B′C′* in Fig. 237.

By using two single-phase regulators, the voltages of two phases are regulated independently of each other and in accordance with their individual requirements, as indicated in Fig. 239. The generator voltage is again represented by *ABC* and the regulated voltage by *AB′C′*. It is obvious that the voltages *AC* and *AB* can be properly adjusted and that, as these voltages are increased or decreased, the voltage *CB* is also varied. *CB* cannot, however, be independently adjusted, but depends on the adjustment of *AB* and *AC*.

By using three single-phase regulators as indicated in Fig. 240, the voltages of all three phases are varied in

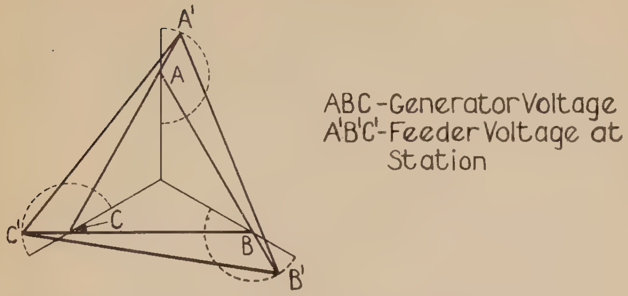


Fig. 238
Voltage Compensation Obtainable with a Three-Phase Regulator

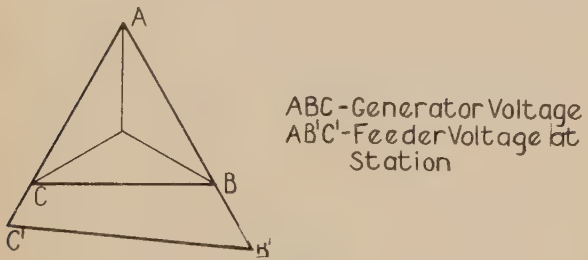


Fig. 239
Voltage Compensation Obtainable with Two Single-Phase Regulators

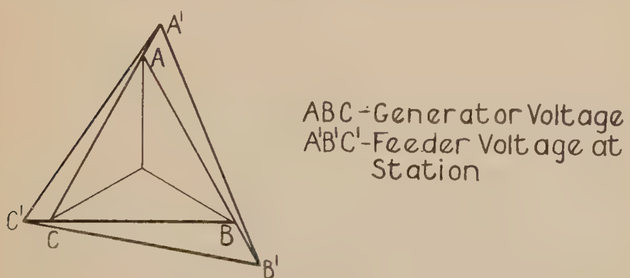


Fig. 240
Voltage Compensation Obtainable with Three Single-Phase Regulators

accordance with the demand of the individual phase requirements. The individual phases are not, however, controlled solely by the individual regulators for the

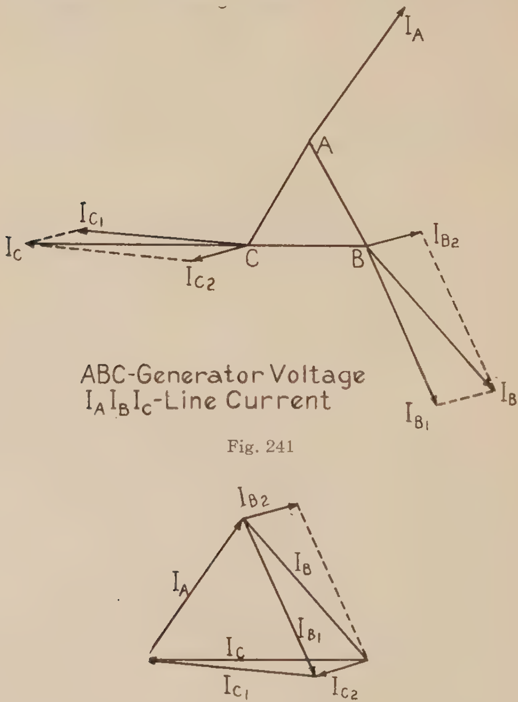


Fig. 241

Fig. 242

Figs. 241 and 242
Vector Analysis of a Three-Phase Unbalanced Load

reason that the movement of any one regulator affects the voltage of the adjacent phase, but in a smaller degree. If the movement of any regulator changes the voltage of the adjacent phase sufficiently to cause the regulator in this phase to require adjustment, the voltage of the third phase

will also be affected, but in a still lesser degree. Any considerable change in load on one of the phases may therefore require a voltage adjustment by all three regulators, but "hunting" as generally understood does not occur.

Line Resistance and Line Reactance

The actual value of line resistance and line reactance must be determined either by calculation or by test. The ohmic and reactive line drop for one conductor is 58 per cent of the value between conductors.

Unbalancing of Current

The actual values of the currents in the three lines must be known. The amount of unbalancing is sometimes given in per cent, but this does not, however, give sufficient data. Assuming the per cent unbalancing to be equal to the maximum deviation from the average value divided by the average value, and further assuming as an illustration an unbalancing of 15 per cent, then, if the average value is 100, one current value is either 85 or 115. In the former case, the other two currents may have any value between 100 and 115, and in the latter case, they may have any value between 85 and 100, the average of the three current values in both cases being 100. Hence, in addition to the unbalancing in the load, it also is necessary to know the nature of the load, so that the currents in the three lines may be calculated or estimated.

In the general solution of the problem, advantage may be taken of the fact that unbalanced three-phase currents can always be resolved into two components, namely, one balanced three-phase and one single-phase current.

This may be demonstrated by the use of Figs. 241 and 242 in which I_A, I_B and I_C in Fig. 241 represent the line currents in the usual manner. The vector sum of the currents in any three-phase system is zero, and the currents must therefore form a closed triangle as in Fig. 242. By selecting any side of the triangle as a base, each of the other two sides may be resolved into two components, one of which, for each phase, will represent a current equal in value to the current selected as the base and displaced therefrom by 120 degrees; that is, the unsymmetrical triangle may be resolved into a symmetrical triangle representing a balanced three-phase current and a single-phase current.

In Fig. 242, I_A has been selected as the base. I_B is resolved into I_{B_1} (equal to I_A and displaced therefrom by 120 degrees) and I_{B_2}, whereas I_C has been resolved into I_{C_1} (also equal to I_A and displaced therefrom by 120 degrees) and I_{C_2}. As indicated by the diagram, I_{B_2} is equal and opposite in direction to I_{C_2}. These components therefore represent the single-phase current, whereas I_A, I_{B_1} and I_{C_1} represent the balanced three-phase current.

Any one of the three-phase currents may be selected as the base, and in each case the unbalanced current will have the same value but a different phase displacement. However, by selecting the smallest current as a base, the single-phase current will be lagging. This is the preferable arrangement for working out the problem.

Power-Factor of Load

The power-factor of the load should be known. As indicating power-factor meters are designed for use on approximately balanced circuits only, it is preferable to estimate the power-factor of both the balanced and unbal-

anced components of an unbalanced load. The power-factor at the load is higher than at the generator due to the reactance of the lines. The load power-factor should therefore be corrected so as to include the line, the correction being obtainable from the line and load data.

Phase Rotation

As will be shown, the phase rotation has an important bearing upon the regulation obtainable, so that the phase rotation must be known.

Phases to be Regulated

It is not always apparent what phase or phases should be regulated to obtain the best average result, and it is therefore necessary to determine this point by calculation or by trial.

Predetermination of Voltage Drop

As an illustration of the method of predetermining the regulation obtainable by the three-phase regulator, by two single-phase regulators, and by three single-phase regulators, the following three-phase feeder having an unbalanced load, as designated, may be assumed.

Length of line	3 miles
Conductor No. 00 B.&S.	0.365 in. diam.
Conductor spacing	12-in. triangle
Voltage (normal)	2300 volts
Frequency	60 cycles
Current (normal)	150 amp.
Unbalancing	15 per cent
Motor-load current	50 per cent
Lamp-load current	50 per cent
Power-factor of motor load	75 per cent
Power-factor of lamp load	100 per cent

From the preceding conditions and by the applications of resistance and reactance tables to be found in any

good electrical handbook, the following data may be obtained:

Resistance per conductor (3 miles)	1.21 ohms
Reactance per conductor (3 miles)	1.61 ohms
Resistance drop per conductor (150 amp.)	181 volts
Resistance drop between lines (150 amp.)	313 volts
Resistance drop between lines in per cent	13.6
Reactance drop per conductor (150 amp.)	242 volts
Reactance drop between lines (150 amp.)	417 volts
Reactance drop between lines in per cent	18.1

As the current values in the three lines are not given, the extreme case for a 15 per cent unbalancing will be assumed; i.e.,

$$I_A = 85 \text{ per cent} = 127.5 \text{ amperes}$$
$$I_B = 100 \text{ per cent} = 150.0 \text{ amperes}$$
$$I_C = 115 \text{ per cent} = 172.5 \text{ amperes}$$

By means of the graphic method shown in Fig. 242 (drawn to scale) and using the smallest current (viz, 127.5) as the base, the three currents are resolved into a balanced three-phase component of 127.5 amperes and an unbalanced component of 46 amperes.

It has been assumed that the currents are made up of approximately 75 amperes balanced motor current at 75 per cent power-factor, and the remainder, of unbalanced lamp current at 100 per cent power-factor. If the load were balanced, and equal currents were taken by the motor at 75 per cent power-factor and by the lamps at 100 per cent power-factor, the combined power-factor of the load would be 93 per cent as shown graphically in Fig. 243. The power-factor at the generator bus may now be approximated as follows:

The voltage at the generator should be assumed to be 100 per cent. In Fig. 244, OA represents the direction of the load current, and as the average power-factor of the load has been found (from Fig. 243) to be 93 per cent, OB should be constructed so as to represent the direction of

the load voltage, that is, so that cos ϕ equals 0.93. From the line data given, the resistance drop is equal to 13.6 per cent and the reactance drop is 18.1 per cent.

At some point on OB, as at B, IR and IX should be constructed so as to be in phase with and at right angles

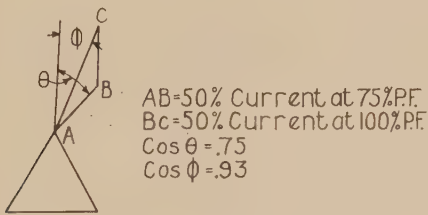


Fig. 243

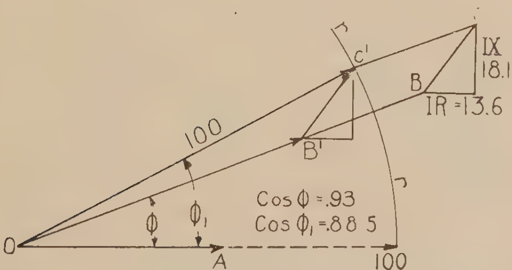


Fig. 244

Figs. 243 and 244
Vector Analysis of the Power-Factor of an Unbalanced Load

to the direction of the current. BC then represents the line drop in value and in direction. BC combined with some value of OB must equal the generator voltage; i.e., 100 per cent. By drawing the arc $r-r$, with O as a center and a radius equal to 100, and by moving BC along OB until point C coincides with the arc as at C', then OB' represents

the load voltage, $B'C'$ the line drop, and OC' the generator voltage. From this voltage and the current OA, the power-factor at the generator is found to be 88.5 per cent which would be correct if the load were balanced. It would be

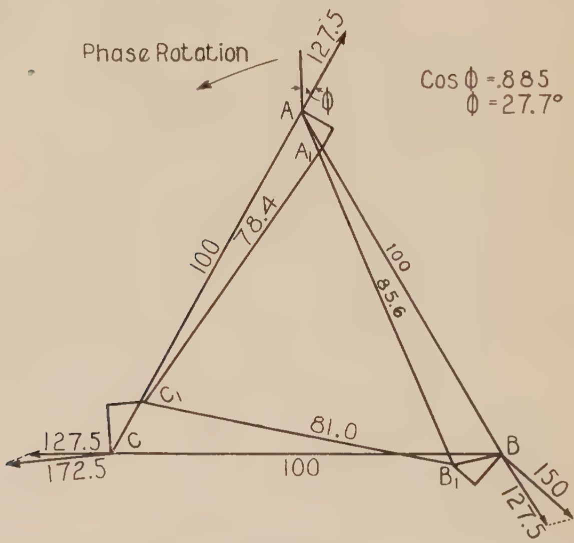


Fig. 245
Vector Analysis of Three-Phase Feeder Carrying an Unbalanced Load (Counterclockwise Phase Rotation)

possible (but more complicated) to determine the exact power-factor, but the method given has been found to be sufficiently accurate for all practical purposes.

From the data now available, the relation between the generator voltage and the line current may be derived graphically as shown in Fig. 245 for counterclockwise phase rotation and in Fig. 246 for clockwise phase rotation.

In making these diagrams, the line currents are resolved into a balanced three-phase component and an unbalanced single-phase component as shown in Fig. 242.

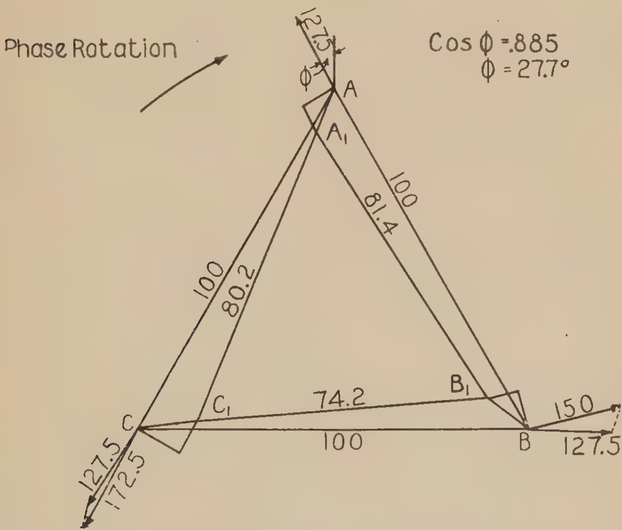


Fig. 246
Vector Analysis of Three-Phase Feeder Carrying an Unbalanced Load (Clockwise Phase Rotation)

The balanced three-phase component is then drawn at an angle to the voltage as indicated by the power-factor of the circuit at the station bus and as determined from Fig. 244. The unbalanced single-phase component is then drawn at the same angle to the balanced three-phase component as found by Fig. 241, and the two components are combined so as again to give the resultant line current with which the investigation was started. The resultant currents are

now, however, at the proper phase angle to the voltage so that the voltage drops in the individual lines may be determined, as well as the voltages at the ends of the line or at the load.

The results of the investigation are given in Table I and show that in a three-phase feeder with unbalanced load, the calculated voltage at the end of the line will depend on the phase rotation. In order, therefore, to determine this voltage, the phase rotation must be known.

TABLE I

VOLTAGE AT END OF FEEDER IN PER CENT OF NORMAL VOLTAGE

(No Voltage Regulation)

PHASE VOLTAGE	VOLTAGE AT END OF FEEDER IN PER CENT OF NORMAL VOLTAGE	
	Counterclockwise Phase Rotation	Clockwise Phase Rotation
A_1B_1	85.6	81.4
B_1C_1	81.0	74.2
C_1A_1	78.4	80.2
Average	81.7	78.6

Regulation Obtainable with a Three-Phase Regulator

In order to determine the regulation obtainable with a three-phase automatic regulator when controlled from the various phases, it is now necessary to assume only that the phase voltage controlling the contact-making voltmeter is 100 per cent. Then each of the other phase voltages should be corrected by its deviation from the original voltage of the phase selected as given in Table I. The voltages across the different phases so obtained are given in Table II.

TABLE II

VOLTAGE AT END OF FEEDER IN PER CENT OF NORMAL VOLTAGE
(Regulation by a Three-phase Automatic Induction Regulator)

Regulated from Phases	Phase Voltage	Voltage at End of Feeder in Per Cent of Normal Voltage: Counterclockwise Phase Rotation	Clockwise Phase Rotation
A and B	A_1B_1 B_1C_1 C_1A_1	100.0 95.4 92.8	100.0 92.8 98.8
B and C	A_1B_1 B_1C_1 C_1A_1	104.6 100.0 97.4	107.2 100.0 106.0
C and A	A_1B_1 B_1C_1 C_1A_1	107.2 102.6 100.0	101.2 94.0 100.0

From the foregoing table, it is evident that there is a considerable variation from normal in the voltage of two of the phases and that the best results are obtained by connecting the control across phases C and A, and by using clockwise rotation. For this connection, one phase is 1.2 per cent above normal and the other is 6.0 per cent below normal.

Regulation Obtainable with Two Single-Phase Regulators

The results obtainable by the use of two single-phase regulators are determined by the method shown in Fig. 247. Figs. 245 and 246 are used as a basis because they give the voltage drop in the line and the unregulated voltage at the load. In Fig. 247, the single-phase regulators are connected across phases A and C, and A and B, and in series with the lines carrying currents I_C and I_B respectively. The requirements are that A_1C_1 and A_1B_1 be each increased to 100 per cent by means of the regulators. The voltages induced in the regulators are, however, in phase with the

voltages at the bus; that is, in phase with AC and AB respectively. In order, therefore, to determine the value of C_1B_1 after A_1C_1 and A_1B_1 are each increased to 100 per cent, the voltage drop in each of the phases regulated

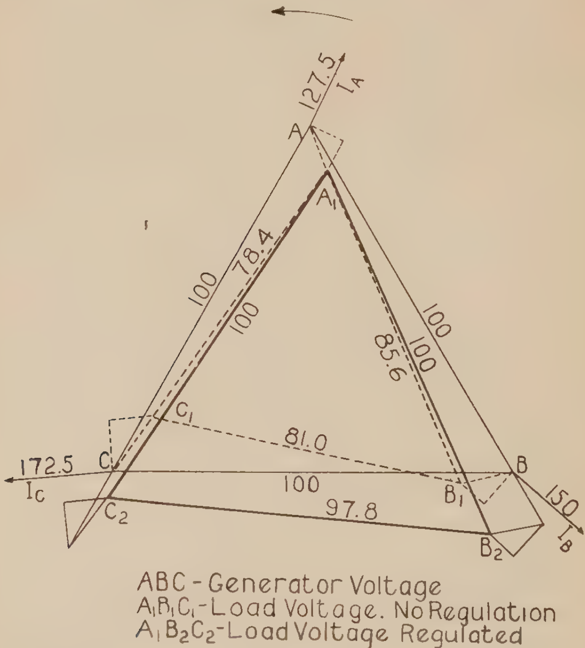


Fig. 247
Vector Diagram of Two Single-Phase Regulators on a Three-Phase System (Phase Rotation Counterclockwise)

(that is, C_1C and B_1B) is moved along the bus voltage AC and AB respectively, maintaining the same angular position thereto until A_1C_1 and A_1B_1 are each 100 per cent. The resultant value of C_1B_1 is represented by C_2B_2 which is the voltage obtainable on the unregulated phase.

Table III shows the voltages obtainable by using two single-phase regulators. As indicated, the best results are obtained by regulating phases AB and AC with a counter-clockwise rotation, in which case phase BC (the unregulated phase) is only 2.2 per cent below normal.

TABLE III

VOLTAGE AT END OF FEEDER IN PER CENT OF NORMAL VOLTAGE

(Regulation by Two Single-phase Automatic Induction Regulators)

REGULATED FROM PHASES	PHASE VOLTAGE	VOLTAGE AT END OF FEEDER IN PER CENT OF NORMAL VOLTAGE	
		Counterclockwise Phase Rotation	Clockwise Phase Rotation
A and B A and C	A_1B_1	100.0	100.0
	B_1C_1	97.8	93.3
	C_1A_1	100.0	100.0
B and A B and C	A_1B_1	100.0	100.0
	B_1C_1	100.0	100.0
	C_1A_1	95.5	101.8
C and A C and B	A_1B_1	105.5	104.0
	B_1C_1	100.0	100.0
	C_1A_1	100.0	100.0

Results Obtainable with Three Single-Phase Regulators

It is self-evident that, by the use of three single-phase regulators, normal voltage is obtainable across each phase at the load and regardless of the unbalancing. That is, results are obtainable under all conditions as given in Table IV.

TABLE IV

VOLTAGE AT END OF FEEDER IN PER CENT OF NORMAL VOLTAGE

(Regulation by Three Single-phase Automatic Induction Regulators)

REGULATED FROM PHASES	PHASE VOLTAGE	VOLTAGE AT END OF FEEDER IN PER CENT OF NORMAL VOLTAGE	
		Counterclockwise Phase Rotation	Clockwise Phase Rotation
A and B	A_1B_1	100.0	100.0
B and C	B_1C_1	100.0	100.0
C and A	C_1A_1	100.0	100.0

Checking Calculations

Although the regulation obtainable by the use of one three-phase and two single-phase regulators is given for both right-handed and left-handed phase rotation, it is obvious that the phase rotation of any system is fixed and that the choice of the regulation is therefore limited as follows:

For regulation with a three-phase regulator, the control may be taken from phases 1 to 2, 2 to 3, or 1 to 3. For two single-phase regulators, any two of the phases may be regulated.

In using a three-phase regulator, the calculations may readily be checked by changing the connection of the regulator auxiliaries so as to obtain the voltage control from between successive phases; but, in using two single-phase regulators, the connection of the regulators themselves must be changed. There are, however, only three combinations, and, for convenience and to avoid changing the phase rotation of the system, the connections given in Fig. 248 are suggested for trial.

General Applications

Commercial circuits necessarily supply power to loads of varying power-factor, and the total power supplied is

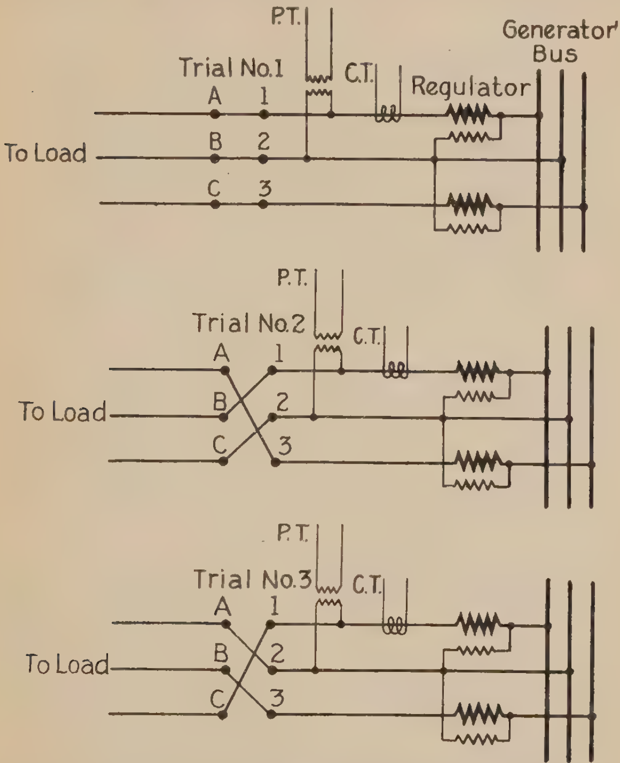


Fig. 248
Connections of Two Single-Phase Regulators on a Three-Phase Three-Wire System

more or less unbalanced during different periods. In order, therefore, to obtain a more comprehensive idea of the regulation obtainable, Fig. 249 has been prepared on the

assumption that both motor-load current and lamp-load current vary so that the motor current is always equal to the balanced part of the lamp current; that is, the

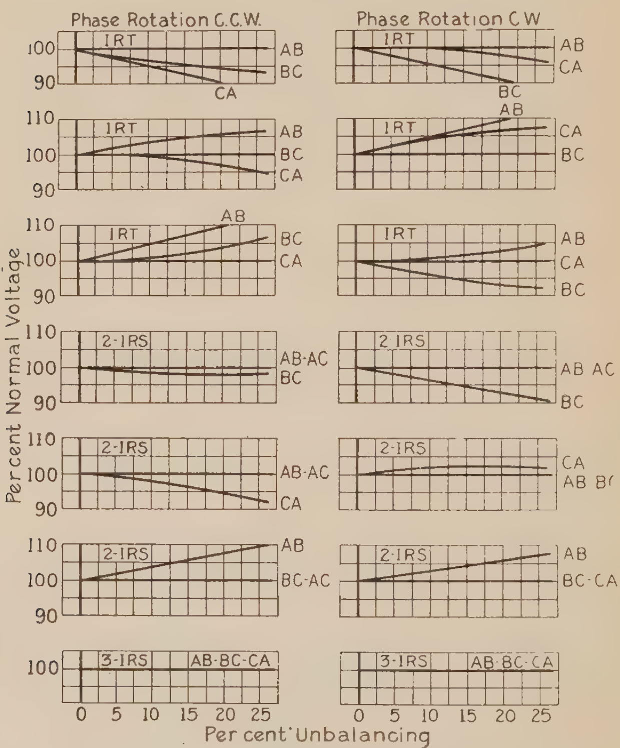


Fig. 249
Voltage Regulation of a Three-Phase Feeder

power-factor of the balanced current component remains constant at 88.5 per cent. Similar curves may be calculated for any other combination of a motor and lamp load. It

will be found that, as the power-factor of the balanced current component decreases, the regulation obtainable on two phases of the feeder controlled by a three-phase regulator and the unregulated phase of a three-phase feeder controlled by two single-phase regulators becomes poorer, and that as the power-factor increases, the regulation is improved. In general, it may be assumed that, as the power-factor of a feeder decreases, the motor load increases and the lighting load decreased. Hence, it may be assumed that the unbalancing decreases. As indicated in Fig. 249, the less the unbalancing, the more uniform is the voltage regulation on all phases.

The change in the power-factor of the load on the phase or phases across which the regulator control is connected is compensated for by the line drop compensator so that the voltage of this phase or these phases is always correct. With an unbalanced load or power-factor, a discrepancy will, however, always exist in the voltage across the other phase or phases, depending on the conditions enumerated and discussed. The selection of the means of regulation therefore depends entirely on the allowable deviation in the load voltage from the normal voltage.

As indicated in Fig. 249, a three-phase regulator does not give accurate voltage regulation on all three phases unless the load is balanced. Two single-phase regulators give much better regulation, whereas three single-phase regulators give perfect regulation regardless of the phase rotation. If, therefore, the load is unbalanced and perfect regulation is not required, it would seem preferable to use two single-phase regulators, for if the requirements should change, a third regulator could be added and perfect regulation obtained.

Conclusions

A three-phase feeder carrying a balanced load may be properly regulated on all three phases by:

One three-phase regulator,
Two single-phase regulators, or
Three single-phase regulators.

A three-phase feeder carrying an unbalanced load can be properly regulated on all three phases by three single-phase regulators only.

A three-phase feeder carrying an unbalanced load not requiring accurate regulation of all phases should preferably be regulated by two single-phase regulators, so that if conditions change and perfect regulation should later be required, such regulation can be obtained at a minimum expense by the installation of a third single-phase regulator.

Comparative Kv-a. Capacities of Regulators

In considering the regulation of a three-phase three-wire system, the combined kv-a. capacity of single-phase regulators is somewhat greater than the kv-a. capacity of a three-phase regulator of the same current rating and voltage range because the voltage induced in the single-phase regulators is in phase with the voltage across the phases and out of phase with the phase voltage of the feeder by 30 degrees (see Fig. 229). This phase displacement must therefore be compensated for by an additional over-ratio in the regulator voltage.

Table V gives a comparison and the requirements of the various arrangements of regulators whereby a ± 10 per cent voltage range can be obtained on a 2300-volt 150-amp. three-phase three-wire feeder. It is assumed that the load voltage required is 2300 volts and that the bus voltage is 2530 volts so that full advantage can be taken

of the total range of the regulator. At 2530 volts on the bus and with 150 amperes flowing in the line, the kv-a. of the feeder is 656.

TABLE V

REGULATION	REGULATOR VOLTAGE PER PHASE WINDING	LINE CURRENT	REGULATOR KV-A.	
			Total	Per Cent of Feeder
One three-phase regulator......	146	150	$146 \times 150 \times 3 = 65.6$	10.0
Two single-phase regulators.....	253	150	$253 \times 150 \times 2 = 75.9$	11.6
Three single-phase regulators for three-wire distribution......	1684	150	$168.4 \times 150 \times 3 = 75.9$	11.6

It should be noted that when using three single-phase regulators, the voltage range required in each regulator is only 6.7 per cent of the voltage across the phases. However for the sake of standardization, it is preferable to use standard 7.5 per cent regulators so that the requirements can be satisfied by regulators of standard design.

In the regulation of a three-phase four-wire system, with the regulator excitation obtained from between the neutral and the phase, the combined kv-a. capacity of the three regulators is equal to that of a single three-phase regulator.

The primary voltage of each regulator is $\frac{100}{1.73}$ or 58 per cent of the voltage between phases, and the secondary voltage of the regulator is in phase with the phase voltage. The voltage range of the regulator therefore corresponds to that required by the feeder to be controlled; that is, to

produce a voltage range of ±10 per cent requires three 10 per cent regulators.

Voltage Regulation of Two-Phase Feeders

Power may be distributed from a quarter-phase generator or bus by either three or four wires. In the

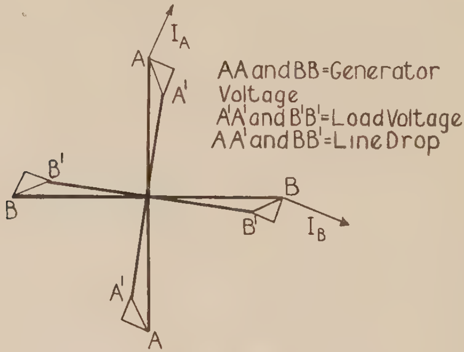


Fig. 250
Vector Diagram of a Quarter-Phase Four-Wire System

four-wire system, each phase is independent of the other and the system may therefore be considered as consisting of two single-phase systems displaced by 90 degrees. In the three-wire system, the two phases are, however, connected at one end, the line from this common connection carrying the current of both phases.

Figs. 250 and 251 represent the two arrangements and show the voltage drop in each case with the same current and power-factor load on each phase. The diagrams are drawn to scale. The load is balanced and the power-factor of the load on each phase is assumed as 93 per cent. In Fig. 250, the IR and IX drop are each assumed to be 10 per cent per line (that is, 20 per cent total), and in Fig. 251, the common line is assumed to be of the same

section as the other two. The drop in this common line is therefore 14.1 per cent for both the ohmic and reactive drops, and is so shown. The diagrams are shown for

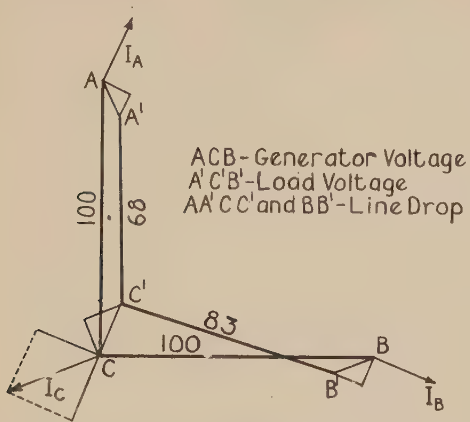


Fig. 251
Vector Diagram of a Quarter-Phase Three-Wire System

left-handed rotation only, for in the quarter-phase system the direction of rotation is immaterial inasmuch as the results are identical in either case.

Four-Wire Systems

It is obvious from Fig. 250, that with a balanced current load of the same power-factor on each phase, proper regulation is obtainable with two single-phase regulators or with a quarter-phase regulator; but that, if the load is unbalanced or the power-factors of the loads on the phases differ, only single-phase regulators will produce correct voltage compensation. With a balanced load and power-factor, the angular displacement between phases remains constant (that is, 90 degrees), but the angular

displacement between the phases will be varied to some extent by any difference in either the current load or the power-factor of the load on the two phases.

The determination of the regulation obtainable is much simpler than with three-phase distribution, for in the present case, each phase may be considered as an independent single-phase system. The current in each phase can be measured directly and the power-factor also can be measured directly or estimated for each phase.

The boost or lower obtainable on the two phases will always be at right angles to each other whether single-phase or quarter-phase regulators are used and regardless of the unbalancing of the load. With single-phase regulators, the boost or lower is always in phase with the line voltage.

With the quarter-phase regulator, the secondary voltage is in phase with the line voltage in either maximum position only, as in a three-phase regulator. The voltage is constant for all positions of the regulator, that is, the voltage range is obtained by a phase displacement as in the three-phase design.

The choice between two single-phase regulators and a quarter-phase regulator then depends on the maximum unbalancing of the load, on the difference in the power-factor of the load on the two phases, and on the allowable voltage difference across the two phases.

Three-Wire Systems

Fig. 251 shows the same load condition as illustrated in Fig. 250, except that it is for a three-wire distribution. Although the generator voltages are equal on both phases and displaced by 90 degrees, the load voltages are unequal and no longer at right angles. With 100 per cent voltage

at the bus, and for the line constants assumed, the unregulated voltage of phase $A'C'$ is approximately 68 per cent of normal, at full load, the voltage of phase $C'B'$ is approximately 83 per cent of normal, and the phase displacement

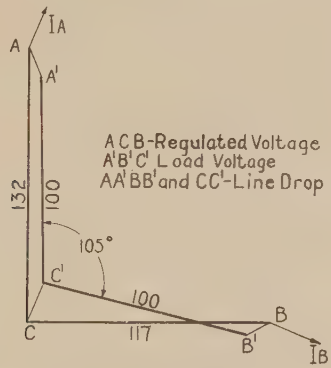


Fig. 252
Vector Diagram of a Quarter-Phase Three-Wire System with Proper Voltage Compensation

is about 107 degrees. The phase voltages can be equalized by means of a single-phase regulator across each phase, the results obtainable being shown in Fig. 252, but the angular displacement of the phases cannot be corrected thereby.

Fig. 253 shows the effect of the power-factor of the load on the voltage drop in the two phases, the curves indicating the total voltage drop per phase and the resultant voltage across each phase at the load. The load is 100 per cent and balanced, and at this load, the resistance and the reactance drops are each 10 per cent in each outside phase line and 14.1 per cent each in the common return; that is, the conditions are identical with those illustrated in Figs. 251 and 252. From the curves given, it is evident that for this particular line and load, the total effective voltage

drop in the phases is identical only with a load power-factor of 71 per cent, that is, with the current and voltage displaced by 45 degrees. This common point varies in position with different ratios of line resistance and line reactance,

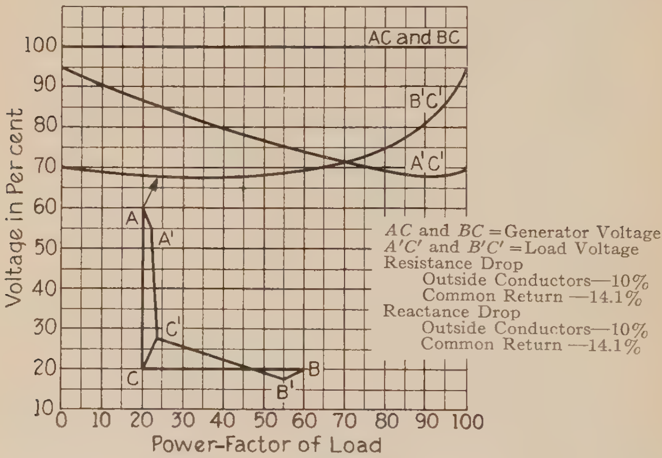


Fig. 253
Voltage Curves for Two-Phase, Three-Wire Feeders with Balanced Load and Variable Power-Factor

and necessarily, also, with an unbalancing of load and power-factor. If, for instance, the line resistance is greater than the line reactance, then with a balanced load, the voltage drop in the two phases will be equal at a power-factor which is higher than given. At zero line reactance, the voltage drop will be equal at 100 per cent power-factor, and at zero line resistance, the voltage drop will be equal at zero power-factor.

It is therefore evident that a quarter-phase regulator is, in general, unsuited for the regulation of a quarter-phase three-wire feeder and that two single-phase regulators must be used to obtain equal voltages at the load.

SECTION XXV

INSTALLATION AND OPERATION

Shipments

Regulators are usually shipped completely assembled and in crates as illustrated in Fig. 254. Skids are provided to facilitate transportation, and if the regulators are handled with a crane, the sling should be securely attached, preferably under the skids.

Auxiliaries for the regulator are always crated separately.

With each regulator, sufficient oil is shipped in hermetically sealed drums.

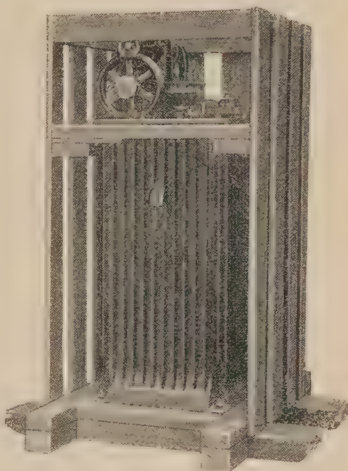


Fig. 254
Method of Crating Voltage Regulator

Instructions for installing are always attached to each regulator, and no attempt should be made to connect the regulator and its auxiliaries without referring to the proper diagram of connections.

In uncrating the regulator and its auxiliaries, the material should always be checked and the parts examined. If parts are missing or damaged, the transportation company or the District Office should be notified.

Storage

If the apparatus is not to be installed immediately after its receipt, it should be stored in a dry and clean

place. Machined parts are oiled before shipment to prevent rusting, and if the apparatus is to be stored for any considerable period, it should be inspected from time to time for rust.

Before water-cooled regulators are shipped, all the water is removed from the cooling coil and the ends of the coil are covered by pipe caps. If the regulator is stored after it has been in service, the same precautions should be taken to prevent water from freezing in the coils and breaking them. All modern oil and water-cooled regulators have the water cooling coils arranged so as to be self-draining. However, if not so designed, the water can be removed by blowing hot air through the cooling coils. If this is not feasible, as much water as possible should be removed by compressed air, and the coils should then be filled with alcohol.

Checking Requirements

Before installing the regulator and its auxiliaries, the name plates should be checked to see that the apparatus is suitable for the circuit which it is to control. The points to be checked are the voltage, frequency, and ampere capacity.

Variations in Voltage

Regulators should not be used on any primary voltage or frequency differing more than 10 per cent from that for which they were designed, because an increase in voltage or a decrease in frequency increases the magnetizing current and the losses. The deviation of 10 per cent allowed must not occur in both the voltage and the frequency unless the individual effects which these deviations have on the losses tend to neutralize each other. For

instance, a regulator should not be subjected to a 10 per cent increase in voltage and the same per cent decrease in the frequency, but it will operate satisfactorily if both the voltage and frequency are increased or decreased within the amount given.

Foundations

Regulators must be installed on supports which are as rigid as possible. The inherent tendency of all regulators is to vibrate, and unless properly mounted, the vibrations may be transmitted to the supporting structure and cause an objectionable hum. If a solid support cannot be obtained and the hum is appreciable, it is recommended that some elastic material, such as thick felt, be placed under the entire base of the regulator.

Cooling

Regulators should always be installed so as to have good ventilation, and in a place free from dust and dirt.

Before oil-immersed regulators are placed in service, they must be filled with the oil furnished, and it is recommended that they be filled at least 24 hours before voltage is applied. This should be done in order to allow the escape of the air in and around the windings because the presence of air is detrimental to the insulation.

The oil should be tested for dielectric strength before it is used. It should test 22,000 volts in a standard gap consisting of 1-in. disk terminals 0.1 inch apart or 40,000 volts with ½-in. disks 0.2 inch apart.

Water-cooled regulators should have the cooling coils piped to a suitable water supply, with the regulating valve between the supply and the regulator. The water supply

should always be piped to the lower end of the cooling coil so as to insure that the coil is always full of water. (See Figs. 51 and 93.) The discharge of the cooling water should be through a sight-flow indicator. The water used for cooling should be free from sediment and mineral matter so as not to clog the cooling coil. It should also be free from acids and alkalies as both are detrimental to the life of the pipe. Iron cooling coils are satisfactory if fairly good water is available but copper coils are otherwise recommended.

Air-blast regulators should be supplied with clean dry air at a suitable pressure to insure sufficient ventilation. The condition of the air is important, for air laden with dust clogs the air passages and restricts the flow. If, in addition, the air is moist, a breakdown of the insulation may result.

The amount of cooling medium required is given in Section X.

Fuses

It is recommended that a switch, with fuses, be used in the control circuit for the relay switch and operating motor. The fuses are intended as a protection against a dead short circuit only, and they should therefore be of sufficient size so as not to blow due to the starting current of the motor. It is therefore advisable that they should have a current-carrying capacity of from eight to ten times the current rating stamped on the motor name plate.

It also is recommended that the primary of the potential transformer be fused as a protection against short circuits. These fuses should also have a current-carrying capacity of from eight to ten times the rated primary current of the transformer.

Under no consideration should fuses be used in a primary of the regulator, and except in special cases, the use of switches is not recommended. If the primary circuit of a regulator is open, with current flowing in the secondary, a potential much higher than normal may be induced in the primary winding, which potential may injure or break down the primary insulation. In general, in cutting a regulator in or out of the circuit, the feeder should be disconnected.

Grounding

The regulator tank should always be well grounded by a wire not smaller than No. 4 B.&S. gauge. The frame or case of both the potential and current transformers should also be grounded by a wire of not less than No. 12 B.&S. gauge.

The circuit of the contact-making voltmeter as well as that of the motor and relay switch should also be grounded.

The purpose of the ground connections is to remove the static and also to protect the operator in case of a breakdown of the insulation of the high-voltage winding.

Connections

The regulator and the auxiliary apparatus are to be connected in accordance with the specific instructions accompanying the apparatus and not in accordance with the general diagrams given in various publications.

The external wiring should have sufficient current-carrying capacity for the load to be handled and should be of such size as to be mechanically strong.

The diagrams do not show oil switches, auxiliary switches or fuses that may be used advantageously, but

it is recommended that the connections be such that the regulator can be cut in or out of service with minimum disturbance in the feeder.

Checking Connections

All connections should be checked, preferably in the following order:

1. Motor, limit switch, and relay switch;
2. Relay switch and contact-making voltmeter;
3. Contact-making voltmeter and potential transformer;
4. Regulator.

Checking Motor, Limit Switch and Relay Switch

With the main and cutout contacts of the contact-making voltmeter (see Fig. 255) insulated by strips of paper, the switch for the control circuit should be closed. The relay switch is then to be operated by hand and the motor run back and forth and over to the limits to see that the limit switch is connected properly. When the regulator segment reaches the limit, care should be taken to open the relay switch immediately, for if the limit switch is incorrectly connected, the segment may strike the stop pin on the cover with sufficient force to break it.

If the limit switch does not open properly, leads *G* and *H* as well as *K* and *L* (Fig. 68) should be reversed to give correct connections.

The contacts of the relay switch are properly adjusted before leaving the factory, but it is recommended that the adjustment be checked to be sure that the stationary graphite contacts are set forward so as to allow for about 1/8 in. wear. It also should always be determined with certainty that the graphite rods are up against the bottom of the adjusting sleeves.

Checking Relay Switch and Contact-Making Voltmeter

FIRST. Remove the paper strip from between the main left-hand contact and allow the contact to close thus exciting one coil of the relay switch and causing the motor

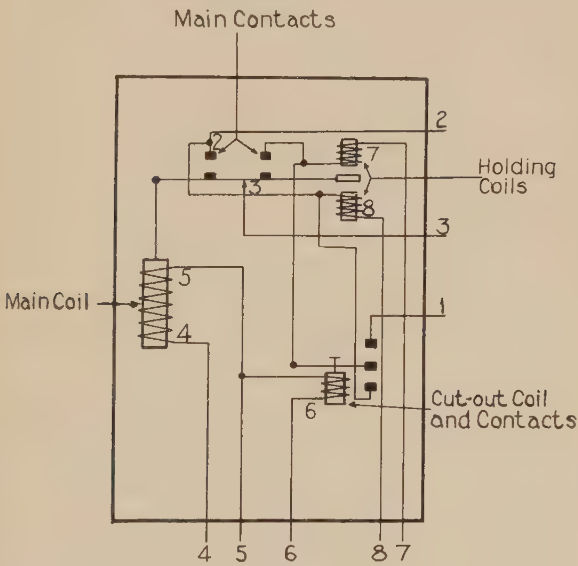


Fig. 255
Connections of Contact-Making Voltmeter

to run. The main left-hand contact of the contact-making voltmeter is made when the feeder voltage is high, so that it should cause the regulator to lower the voltage. If, instead, the regulator should boost the voltage, the lines *1* and *2* (Fig. 109) to the relay switch should be reversed.

SECOND. Remove the paper strip from the main right-hand contact and allow the contacts to close. As the cutout contacts are still insulated, no excitation should be furnished to the relay switch.

THIRD. Remove the paper strips from the cutout contact. As the cutout coil has no excitation, its lower contact is made so that, with the main right-hand contacts closed, the regulator should lower the voltage. The regulator should boost the voltage if the cutout is excited so that its upper contact is made.

Indicators on the handwheel of the regulator show the direction of rotation to boost or lower the line voltage. In general practice, a counterclockwise rotation of the handwheel and the gear segment boosts the line voltage.

If the connections give a wrong rotation of the regulator, the two leads which run direct from the control bus to the limit switch should be reversed.

Contact-Making Voltmeter and Potential Transformer

The connections of the contact-making voltmeter and potential transformer cannot be checked until excitation is applied to the regulator. The regulator should therefore now be connected to the bus, leaving the feeder side open. This connection should be made while the control switch is open and the rotor of the regulator is in the neutral position. Excitation is thus furnished to the potential transformer. If the regulator is of the oil-immersed type, it must be filled with oil before being connected in circuit.

With the levers of the line drop compensator set on points zero (that is, with zero compensation), the excitation of the main coil of the contact-making voltmeter should now be adjusted. An indicating voltmeter should be connected to the feeder side of the regulator and it is usually satisfactory to connect it to the potential transformer used to excite the contact-making voltmeter. The regulator should be adjusted by hand until the voltmeter indicates the voltage that it is desired to hold at the center of distribution.

The connection on the terminal board of the non-inductive resistance in series with the potential winding of the contact-making voltmeter, should then be changed to the terminal stamped with the voltage nearest to the one it is desired to hold on the feeder. For example, if it is desired to hold 113 volts, connection should be made to the 115-volt terminal.

The tension spring of the contact-making voltmeter is now to be adjusted so that the balance arm of the voltmeter will be equidistant from the holding coils. The clearances between the contacts should be adjusted to about $\frac{1}{16}$ in. per side or in such a manner that contact is made for a change of about 1 volt either way from normal as read on the 110-volt indicating voltmeter, the necessary change in the voltage being obtained by turning the regulator by hand.

The next step is to close the control switch, and by operating the balancing arm of the contact-making voltmeter by hand, the regulator should operate. Upon releasing the lever, the contact-making voltmeter should make contact at the opposite side so that the regulator will return to the original position, leaving the voltmeter lever in the midway position.

The amount of over-running of the smaller regulators can be regulated by adjusting the spring tension of the permanent brake. The larger regulators supplied with magnetic brakes require considerably more time to correct for a line voltage change; hence, the brake adjustment need not be so exact as required in the high-speed regulators. The brakes are therefore non-adjustable but designed so that the over-run is well within the desired limits.

Attention should now be given to the holding coils which are connected to the control circuit as shown in the diagram furnished.

The connections should be checked to see that the effect of these coils is to increase the pressure on the contacts.

The cores of the holding coils are threaded and the holding effect can be adjusted by turning the cores, thus changing their projection through the coils as may be required. The cores in the holding coils should be so adjusted that when the main contact is opened the balance arm will move into its normal position, and it should in no case be allowed to make contact on the opposite side as this would cause hunting of the regulator.

After these connections have been checked and the adjustments have been made as outlined, there still remains the adjustment of line drop compensation. This cannot be accomplished until the regulator is connected in service and carries load. The adjustment for line drop compensation in no way interferes with the previous adjustment for normal voltage; that is, the adjustment of the helical spring, contacts and holding coils should not be changed unless it is desired to make a change in the normal adjustment.

Regulator

With the control switch open and with the rotor in the neutral position, connect the regulator to the feeder as shown in the diagram furnished with the regulator.

It is always recommended that the feeder switch be open while the regulator is being connected in the circuit. Exceptions may be made and these are referred to under the heading "Connecting and Disconnecting Regulators".

After the regulator is connected and the feeder switch is closed, the regulator should be operated to its limits to see that it boosts or lowers the feeder voltage as intended.

The phase rotation of polyphase regulators should be checked either now or at some other convenient time. As described in Section VI and illustrated by Fig. 36, it is characteristic of polyphase regulators that, when moved from either limit to the neutral position under load, the primary current will either increase or decrease depending on the direction of rotation of the magnetic field within the regulator. For the sake of reducing the heating, it is desirable that the field rotation be such as to give the minimum primary current.

The secondary terminals of all polyphase regulators are numbered 1, 2, 3, etc. The primary terminals are similarly numbered and should be connected directly to the correspondingly numbered secondary terminals. If the phase rotation of the circuit is 1, 2, 3, and the regulator terminals are connected to correspondingly numbered line terminals, the field rotation in the regulator will be such as to give the minimum primary current. In installing the regulator, this can be checked in the following way:

First. General Electric Company regulators have the terminals marked 1, 2, 3, etc., and the phase rotation is 1, 2, 3, etc., so that if the phase rotation of the system to which the regulator is to be connected is known, the proper connections to the regulator are as stated.

Second. If the phase rotation of the supply system is unknown, it can be determined by the rotation of a motor or by using some special device whose rotation has been determined from a system of which the phase rotation is known.

Third. The easiest way is to connect the regulator in the circuit without regard to phase rotation, and later check the primary current of the regulator, reversing the phase rotation if necessary.

For this purpose, a portable current transformer may be connected in series with one of the primary leads and to an ammeter. The test must be made when the regulator carries an appreciable load. The current in the primary

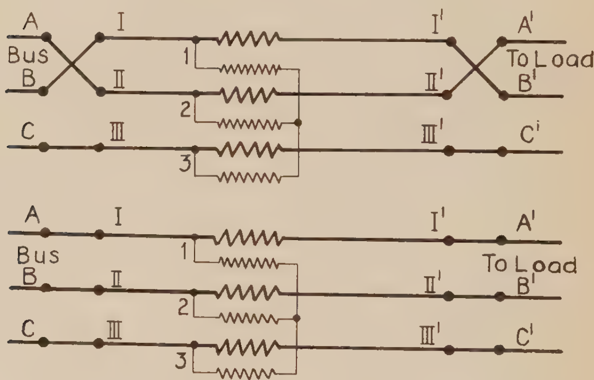


Fig. 256
Connections for Reversal of Phase Rotation of Three-Phase Regulator

should be noted when the rotor is moved from either limit toward the neutral. If the current increases materially, it is a sign that the field rotation is not correct and should be changed by reversing any two leads on both sides of the regulator as shown in Fig. 256.

Adjustment for Line Drop Compensation

Instructions for adjusting the line drop compensator are given in detail in Section XVII.

Connecting and Disconnecting Regulator

While it is always recommended that regulators be connected in or taken out of service by first opening the oil

switch of the feeder, the following methods may be used in cases of emergency:

Single-Phase Regulators

A. Connecting in Service on Live Feeder:

1. Rotate the regulator armature into the neutral position; that is, the segment should be half way between its limiting positions.

2. Open the switch of the control circuit so that the motor can not accidentally change the position of the regulator rotor.

3. Connect both ends of the secondary winding of the regulator to one line of the feeder; that is, the secondary winding becomes short-circuited.

4. Connect the primary winding in shunt with the feeder, thus furnishing excitation for the regulator.

5. Cut the line forming the short circuit for the secondary winding, thus causing the line current to flow through the secondary winding of the regulator.

6. Close the control switch, for the regulator is now ready for service.

B. Disconnecting the Regulator from a Live Feeder:

1. Place the regulator rotor in the neutral position; that is, the segment should be in the mid-position between its limiting positions.

2. Open the switch of the control circuit so that the motor can not accidentally change the position of the regulator rotor.

3. Short-circuit the secondary winding of the regulator, using a "jumper".

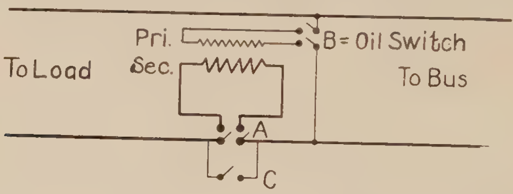
4. Disconnect the primary winding from the line by means of an oil switch.

5. Disconnect the secondary winding from the line leaving the "jumper" to carry the line current.

If, for some reason, it should be desired to cut the regulator in and out of circuit periodically and a switching equipment is provided therefor, it is suggested that the arrangement correspond to the one outlined in Fig. 257.

Polyphase Regulators

Polyphase regulators can not be connected in or cut out of service from live feeders in a manner similar to



TO CONNECT REGULATOR INTO CIRCUIT

Switches *A* and *B* Must be Open
Switch *C* Must be Closed

1. Place Regulator in Neutral Position
2. Close Switch *A*
3. Close Switch *B*
4. Open Switch *C*

TO CUT REGULATOR OUT OF CIRCUIT

Switch *C* Must be Open
Switches *A* and *B* Must be Closed

1. Place Regulator in Neutral Position
2. Close Switch *C*
3. Open Switch *B*
4. Open Switch *A*

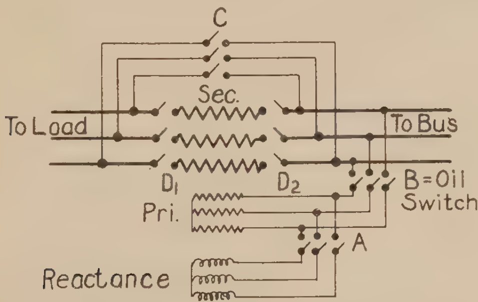
Fig. 257
Connections of Single-Phase Regulator with Cutout Equipment

single-phase regulators without causing a heavy short circuit, and such a method must under no circumstances be adopted.

It is possible by using special apparatus to cut a polyphase regulator in or out of service on a live line, but it is not recommended.

However, in case this is found necessary, it may be provided for by the means illustrated in Fig. 258. The voltage induced in the secondary of a polyphase regulator has a constant value regardless of the relative boost or lower position of the armature. It is therefore necessary to make use of a reactance or a resistance temporarily

connected across either the shunt or series windings (to absorb the induced voltage of the regulator by means of the current in the reactance) before the regulator can be cut out of circuit.



TO CONNECT REGULATOR INTO CIRCUIT	TO CUT REGULATOR OUT OF CIRCUIT
Switches *ABD₁* and *D₂* Must be Open	Switches *A* and *C* Must be Open
Switch *C* Must be Closed	Switches *BD₁* and *D₂* Must be Closed
1. Close Switch *A*	1. Close Switch *A*
2. Close Switches D_1 and D_2	2. Open Switch *B*
3. Open Switch *C*	3. Close Switch *C*
4. Close Switch *B*	4. Open Switches D_1 and D_2
5. Open Switch *A*	5. Open Switch *A*

Fig. 258
Connections of Three-Phase Regulator with Cutout Equipment

As shown in Fig. 258, a reactance is connected across the primary of the regulator before the primary is disconnected from the line. When the primary is disconnected, the current flowing in the series winding of the regulator induces a corresponding current in the primary winding but which now flows through the reactance instead of through the feeder and thus limits the potentials across both windings to their normal values. The reactance must be able to carry the full primary current while the regulator is being cut in or out of circuit, and must be wound for the potential of the primary winding as it must be connected across the line and in shunt with the regulator before the combination of the two can be disconnected.

However, as the line potential is across the reactance but momentarily, and as it also carries current for only a short time, advantage may be taken of these conditions in designing the reactance.

In using the arrangement shown, the regulator should be in the neutral position so as to avoid changing the line potential by the opening or closing of the switches.

Care of Apparatus

All apparatus must be kept free from dirt and dust, and all rotating parts must be kept well lubricated with mineral oil.

Regulator

The top bearing for the rotor shaft should be well lubricated. A felt ring is located in a recess in the top of the cover to hold the oil.

The gear segment and worm should be lubricated with heavy grease.

The oil wells for the motor bearings and the oil cups for the bearings for the worm shaft should be filled with a good lubricating oil.

The brake pulley should be lubricated occasionally to prevent the leather lining from overheating and binding.

The oil in the regulator should be kept up to the center of the oil gauge. Occasional refilling is required as the oil evaporates slowly. The oil, particularly in regulators on systems of over 5000 volts, should occasionally be tested for dielectric strength. Oil for this purpose should be drawn from the bottom of the tank and if its dielectric strength is found greatly reduced, it should be replaced or treated, preferably by passing it through a filter press until its insulating value is again restored. It is, however, to be noted that the oil level must not be reduced more than a few inches while the regulator is in service.

In water-cooled regulators, care should be taken that condensed water, which is likely to form on the ends of the cooling coils where they are brought out of the tank, is not allowed to get into the oil. Such danger is not present if the coils are brought out of the tank below the oil level. If the cooling coil is above the oil, condensation may be prevented by covering that part of the coil which is inside of the tank and which is above the oil with a thick wrapping of felt.

Regulators cooled by air-blast must occasionally be cleaned to remove the dust which accumulates on the winding and other parts.

Relay Switches

The contacts of the contactor type of relay switch require practically no attention.

Those of the pendulum type of switch should be cleaned and adjusted at such intervals as have been found necessary from practice. These intervals vary from one week to several months, depending on the frequency of operation. The contacts should be smoothed off with a file or sand-paper, and adjusted so that the springs to which the movable contacts are secured will be bent back by an amount corresponding to 1/8 inch forward movement of the contacts when the magnet armature is up against the magnet core.

The bearings for the armature should be oiled occasionally.

Contact-Making Voltmeter

As the contact-making voltmeter is a sensitive instrument, the best service is obtained by keeping it free from dust and dirt. The contacts should occasionally be cleaned and smoothed off by means of a fine clean file or with crocus cloth.

Locating Trouble

Tight Running

If the regulator turns hard, the trouble may be located either in the worm or the bearings of the rotor shaft.

If the binding is in the worm, it may be due to the segment having slipped down on the shaft, and corrective measures can be taken.

If the tightness is not in the worm, it will be necessary to investigate the bearings, and for that purpose, the regulator must first be taken out of service. The procedure then to be followed is:

1. Remove motor and motor support.
2. Remove the set screws from the segment.
3. By means of a jack, force the segment off the shaft. The segment is driven on with a tight fit, and its removal will sometimes necessitate the heating of the hub by means of blow torches.

The next step is to remove the cover. The best method to be followed for the particular design of regulator in trouble can be determined by referring to the sectional diagrams of the various designs of regulators. (Fig. 74 to Fig. 78 inclusive.)

If there is no trouble in the cover bearing, it is undoubtedly in the bottom bearing.

In removing the wooden bushing blocks for the cable leads, care must be taken not to break off the corners as such pieces are likely to wedge themselves between the windings, and damage the insulation on the coils.

If the regulator is assembled in a ribbed cast iron tank having a removable bottom, care should be taken in reassembling to make a tight joint between the bottom and the tank. The contact surfaces must therefore be thoroughly cleaned and all bolts must be drawn up as tight as

possible. A gasket consisting of 0.005-in. paper dipped in shellac may be used to advantage between the tank and the bottom. It is advisable to re-assemble the bottom on the tank in its original position. Before removing the bottom from the tank, it is therefore advisable to mark both tank and bottom.

Oil Leakage

Oil leakage may occur either at the joint between the bottom and the tank, or through the casting. To locate the leak definitely, cover the suspected surface with dry chalk.

If the leak is at a joint, it will be necessary to disassemble the parts, clean all surfaces, and reassemble.

If the casting is spongy, it may be brushed with several coats of shellac each of which should be baked on separately by means of a blow torch, or holes may be drilled in the tank at the points of leakage and then plugged. Both of these methods have been used successfully.

Noise

Noise in regulators is generally due to one of two causes: a non-uniform air gap between the rotor and stator cores; or too much clearance in the bearings.

It is not recommended that a customer attempt to remedy this trouble, and the best course is to return the regulator to the factory for overhauling.

Noisy operation may also be caused by a partial short circuit of the regulator windings. Such a short circuit may not immediately burn out the windings but will cause excessive heating. Hence, if a regulator should become noisy and the heating should simultaneously increase without any increase in the load, it should be taken out of the circuit and tested for short circuits and grounds.

Regulation

If the apparatus does not maintain the voltage for which it was originally adjusted, the following causes should be looked for:

1. Loose screw in contact-making voltmeter.
2. Dirty contacts.
3. Friction in contact-making voltmeter.
4. Friction (possibly in leads of relay switch) or improper adjustment of contacts.
5. Change in location of recording voltmeter or for load added to feeder between station and recording voltmeter.

Repair of Regulator Windings

It is not recommended that a customer attempt to repair a regulator which has failed in service unless he has good repair facilities and can make proper tests after the repairs are made to see that the regulator is in a reliable condition.

Minor repairs or emergency repairs may be made on the premises, and in making them, the following points should be observed:

1. Before disconnecting the regulator, make a sketch of the connections and tag all leads for identification.

2. In inserting new coils, it is recommended that they be warmed slightly to give more flexibility.

3. Do not pound the coils if they are found tight in the slots, but use suitable levers so as not to injure the insulation.

4. Do not use acid in soldering joints; use rosin and tallow.

Particular care should be taken in the case of polyphase regulators not to get the leads exchanged. The following

information applying to a three-phase regulator having a Y-connected primary may be of value.

Referring to Fig. 256, the secondary leads are marked *I*, *II*, *III*; the corresponding primary leads are marked *1*, *2*, *3*.

Correct connections are:

1 to *I*
2 to *II*
3 to *III*

If connected:

3 to *I*
1 to *II*
2 to *III*

the primary field will be displaced 120 degrees from its former position. Hence, it is no longer possible to obtain full values of feeder voltage boost and lower at the extreme positions of the rotor, and the neutral position has also been shifted. The voltages are, however, balanced.

If connections are:

2 to *I*
1 to *II*
3 to *III*

then the primary field is rotating in a reversed direction and the voltage increase or decrease on the three phases of the feeder will be unbalanced.

Installation of Outdoor Regulators

Regulators should be installed so that the automatic accessories are accessible for inspection. Fig. 259 indicates the proper manner of installing the pole type regulator, and a similar arrangement is recommended for the converted station design. The latter design of regulator is not,

however, provided with or arranged for hangers, but it can be mounted on a platform as shown in Fig. 170.

Oil

Outdoor regulators intended for location where the temperature drops below zero degrees F. are furnished

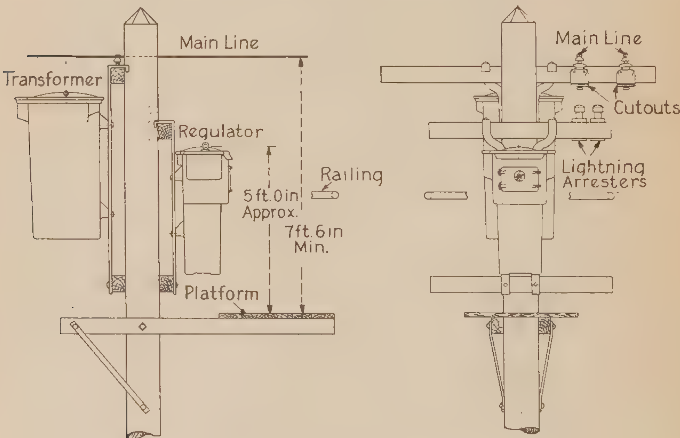


Fig. 259
Pole Type Regulator Mounting

with a special oil of low freezing point. This oil evaporates somewhat faster than the oil used in indoor regulators so that the refilling of the regulator is necessary at somewhat more frequent intervals.

Checking Requirements, Connections, Operations, etc.

Outdoor regulators require the same attention as the station design, and they should have the same care in installation and should likewise be periodically inspected.

Special Instructions for Pole Type Regulators

Pole type regulators should be connected to the line as shown in Fig. 153.

When placing the regulator in operation for the first time, it should be carefully watched for a sufficient time to see that the various parts function properly.

1. See that the fuse plugs for the control circuit are of proper capacity; that is, 6 amperes for a 110-volt control circuit, and 3 amperes for a 220-volt control circuit.

2. See that the motor turns freely, using the knurled knob on the motor shaft extension for turning.

3. See that the regulator turns freely, using the pin in the worm shaft for turning.

4. See that the pawls and triggers are free.

5. See that the dashpot is filled with oil, using the same grade of oil as supplied with the regulator.

6. See that the relay plunger and balance arm operate freely.

7. See that connections are made to the proper tap of the series resistance for the voltage relay, using the tap corresponding to the nearest voltage it is desired to hold. For example, if it is desired to hold 113 volts, connect to the 115-volt tap.

8. See that all the following wearing surfaces are properly lubricated:

(a) Two motor bearings,

(b) Outboard bearings,

(c) Segment,

(d) Rotor bearing under segment,

(e) Worm and gear, by filling the well through the trough.

9. Operate the motor, starting and stopping it several times. It should come to speed quickly and without sparking at the brushes. The combination brush-holder and terminal must be drawn up tight.

The regulator may now be placed in service, and the adjustment for proper voltage regulation should be obtained as follows:

1. If the regulator voltage is too high, tighten up the spring attached to the relay balance arm and vice versa.

2. If the regulator does not hold the voltage within the desired limits, turn the adjusting screw (*J*) shown in Fig. 148. Raising the bearing for the relay arm (*M*) will increase the voltage limit, and vice versa.

The regulator is adjusted before leaving the factory to hold the voltage within 1 per cent limits, and closer regulation is not recommended as it may cause excessive wear of the mechanism.

Connecting and Disconnecting Regulators

While it is always recommended that regulators be connected in or taken out of service by first opening the feeder, the method given for connecting and disconnecting regulators may be followed in cases of emergency.

Care of Apparatus

While the same general instructions apply to the pole type regulator as to the station design, the following additional precautions should be observed.

The mechanism should be kept free from dirt and dust and all wearing parts should be well lubricated. Under ordinary operating conditions, it is not expected that a regulator will need attention more than once every two months,—possibly less frequently, depending upon local conditions.

During the periodical inspections, the following points should be kept in mind:

1. Check up the oil in the tank. It evaporates with time. If the oil level is 2 inches below the lower surface

of the casting which supports the mechanism, more oil should be added so as to raise the level to 1 in. below the casting. Use only special oil of the kind originally furnished with the regulator.

2. See that the oil in the dashpot is clean, and comes up to the proper height (level with the lower section of the dashpot). The lower part of the dashpot can be unscrewed and taken out for cleaning. In replacing, see that it is screwed up perfectly tight against the leather washer.

3. See that the oil well for the motor worm is filled with a good grade of machine oil, and fill all other oil holes.

4. Give the lever of the grease cups for the motor and outboard bearings about four turns, and if the grease is used up, refill with "Tulc" (a special grease).

5. Clean the collector rings of the motor by using a wiper of felt or cloth moistened with light oil, preferably kerosene.

6. Inspect the carbon brushes of the motor and replace them before they are down far enough to pit the collector rings.

Locating Trouble

If the regulator turns hard, the trouble may be located either in the worm and segment or in the bearings for the rotor shaft. If a liberal amount of lubricating oil supplied to the rotor top bearing and to the worm and segment fails to relieve the trouble, it will be necessary to remove the regulator with its mechanism from the tank in order to apply corrective measures. It is, in general, not recommended that a customer attempt to do this, but in case of emergency the following procedure should be adopted:

1. Disconnect the control leads at the fuse block and at the resistance terminal block. Chip out the compound

around the line leads so that they can be pulled through the porcelain bushings, or cut the cables inside of the tank.

2. Remove the two bolts which hold the top frame to the tank.

3. Remove the regulator, with the mechanism, from the tank. This can be done by inserting lifting studs in the two tapped holes provided for this purpose in the regulator frame. The studs should be 5/8 in. in diameter and about 18 in. long. One end of each stud should be threaded for a distance of about 1 in. with a 5/8 in.–16 thread, while the other end should be bent into a hook, or threaded and provided with an eyenut.

4. To determine whether the binding is in the mechanism or in the rotor bearings is now in order, and when the binding has been located, corrective measures should be taken.

In order to remove the mechanism from the regulator, proceed as follows:

(a) Loosen the cap screw in the segment.
(b) Remove the positive stop for the segment from the mechanism support.
(c) Turn the segment counterclockwise until it is free of the worm, and remove the segment from the regulator shaft.
(d) Remove the three bolts which hold the mechanism to the regulator frame.
(e) The base on which all the mechanism is mounted may then be raised so as to clear the shaft.

Special Instructions for the Station Design of Regulator Arranged for Outdoor Service

The operating motor of the pole type of regulator is in continuous operation, and, therefore, this load on the

transformer from which the motor operates is constant. In the station design of regulator the motor is, however, required to start from rest for every change in the regulator

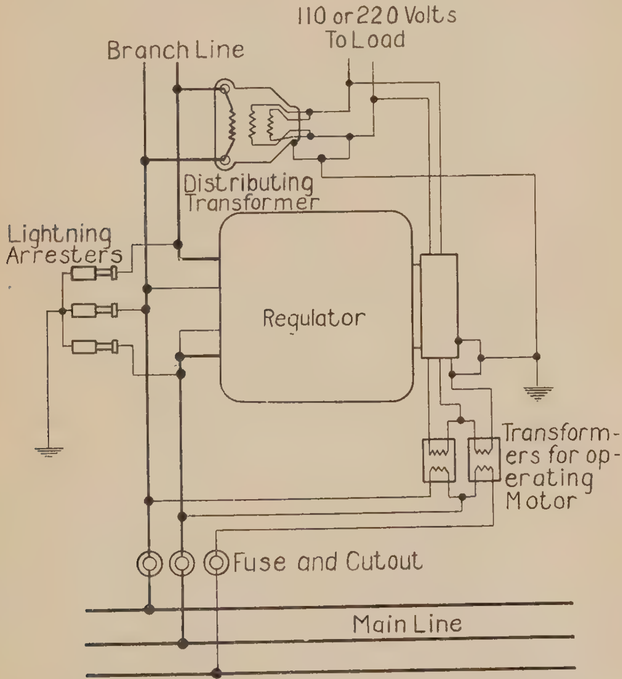


Fig. 260
Connections of Station Design of Regulator for Outdoor Service

adjustment, and at the moment of starting, the motor requires considerably more than the normal running current. This starting current, although it may be small compared with the kv-a. capacity of the transformer, introduces a momentary drop in the transformer voltage. If the contact-making voltmeter is connected in parallel

with the operating motor, this change in the voltage affects the operation of the meter, and more or less hunting may result. It is therefore recommended that, for all such installations, the power for the operating motor and relay switch be obtained from a separate transformer or transformers as illustrated in Fig. 260. These transformers should always be connected ahead of the regulator as shown, and the circuit should be grounded as shown.

Line Drop Compensation for Outdoor Regulators

As outdoor regulators are usually installed on the feeder at or near the center of distribution, current and potential transformers and the line drop compensator are not generally required. They have therefore been omitted from the diagrams. If, however, the regulators are so located that line drop compensation is required, the auxiliaries can be connected in the control system as shown for the station type of regulator.

Drying Out of Regulators

In testing oil-immersed regulators, they are always filled with oil. This oil thoroughly penetrates the windings and, because of the large amount of insulation on the coils, the windings remain filled with oil even after the oil in the tank is withdrawn. All oil-immersed regulators wound for 6000 volts and over are vacuum dried and oil-filled.

Regardless, however, of the precautions taken, it is recommended that regulators wound for 6000 volts and over be dried out by short-circuiting the series winding and applying a sufficient voltage to the primary winding to maintain a coil temperature of 95 deg. C. until all traces of moisture are eliminated.

SECTION XXVI

PROTECTION OF REGULATORS

The relation of a feeder regulator to a line, the voltage of which it is to regulate, is such that the secondary winding of the regulator is virtually an extension of that line, or rather, a series connection between the line and station bus. It is therefore exceedingly important that careful consideration be given to the effect which various disturbances (to which the line may be subjected) have on the regulator. These disturbances may be high voltage, high frequency, or high current, or any combination of the three. They may be considered as follows:

Abnormal High Potentials and High Frequencies

Excessive potentials may occur in feeder lines due to various conditions:

First. Internal to the circuit, such as: short circuits, arcing grounds, operation of switches and circuit breakers, charging of aluminum cell lightning arresters without charging resistances, "phasing in" of generators, and occurrence of resonance. Such disturbances are of comparatively low frequency, less than 50,000 cycles per second.

Second. External to the circuit, due to lighting. Lighting discharges are of various intensities according to the distance of the discharge from the circuit and are usually of high frequency, up to 1,000,000 cycles per second.

Underground feeder lines are subject only to disturbances originating in the system, the results of which may, however, be destructive if the kv-a. capacity of the system is sufficiently great.

Overhead feeder lines are subject to disturbances originating both within the system and externally to it, and some of the former may be caused by the latter.

Combinations of underground and overhead lines are subject to disturbances originating within the system and externally to it, and also to high voltages due to resonance. Experience shows that this combination of feeders is more liable to disturbances than either separately, and that a particularly critical point in the combination is at their junction.

Overhead feeders in districts subject to severe lightning disturbances may be protected to some extent by ground wires carried above the feeder lines on the top of the poles and as a protection against surges of both internal and external origin, it is common practice to connect an aluminum cell lightning arrester to the bus of the distributing station. This arrester will be effective in discharging disturbances arising in the station and in the various feeder lines emanating from the station, provided there is no obstruction between the arrester and the source of trouble to retard the surge and prevent the action of the arrester. Such an obstruction may absorb or reflect the disturbance, and in the latter case, may not only defeat the object of the arrester, but it may magnify the disturbance beyond the safety point and cause a breakdown in the circuit.

Current transformers, current-limiting devices and feeder regulators may act as such obstructions because of their reactance. The danger of breakdown in such apparatus must therefore be given consideration. Because of their respective mechanical designs, current transformers and current-limiting reactances can be more readily insulated to withstand abnormal strains between turns and layers than can regulators.

Safety Factor of Insulation

Regulator windings are of the same general design as those used in generators and motors, and are similarly

assembled in the slots of the core. A design to be satisfactory in operation and cost should have a fairly definite relation between the size of the core and the windings. This relationship fixes the ratio of copper to the insulation in and around the coils. Properly designed regulators are insulated so that, regardless of the nature of the disturbances, the likelihood of an internal breakdown of the insulation is no greater than the likelihood of a breakdown to ground. In regulators designed by the General Electric Company, the amount of insulation to ground is such that, when referred to the line voltage, it has an instantaneous safety factor of approximately ten. An equalization of the internal and external insulation as specified generally requires, however, a much higher safety factor internally, and it may be several hundred when compared to the normal induced voltage between turns and layers.

Insulation having the factor of safety specified is not sufficient, however, to withstand the maximum voltage disturbances likely to occur on some distributing systems, nor is it economical or practical to provide all windings with such an amount of insulation because such disturbances are the exception rather than the rule and because a better and safer protection can be provided external to the regulator at less cost.

Protective Devices

The protective devices available and their particular functions in the protection of feeder lines and regulators are as follows:

1. Multigap, aluminum cell, or oxide film arresters at the point where the feeder enters the station.

2. An aluminum cell or oxide film lightning arrester on the feeder bus as a protection against excessive voltages on the bus.

3. By-pass cells across the series windings of the regulator to provide a passage of low resistance for high frequency surges of a certain critical voltage, thereby allowing these disturbances easily to reach the bus and be disposed of by the bus arrester.

4. Choke coils or sometimes power-limiting reactors serving for protection against excessive short-circuit current, installed on the feeder side of the regulator to smooth out entering steep wave fronts and to hold back the lightning discharge until the multigap arrester on the feeder and ahead of the choke coil has time to discharge the surge to the ground.

The protection to install on a system depends: first, on whether the lines are underground, overhead, or a combination of the two; and, second, whether or not the system is subject to more than the normal disturbances to be expected under ordinary conditions of operation.

The subject may therefore be considered under these three headings, considering also the protection necessary for normal conditions and the additional protection advisable for abnormal disturbances. The following recommendations are submitted:

For Cable Feeder Lines

NECESSARY—(1) Aluminum cell or oxide film lightning arrester on the feeder bus.

ADVISABLE —(2) By-pass cells across the secondaries of each regulator connected in feeders which are subject to unusual disturbances (as, for example, frequent switching).

For Overhead Feeder Lines

NECESSARY—(1) Aluminum cell or oxide film lightning arresters on the feeder bus.

(2) Choke coil in series with the series winding of the regulator and on the line side of it.

(3) Multigap arresters and choke coils on each feeder on the line side of the regulator.

ADVISABLE—(4) By-pass cells across the secondaries of each regulator connected in feeders which are subject

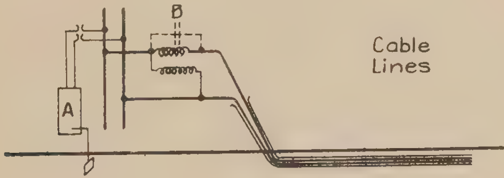


Fig. 261

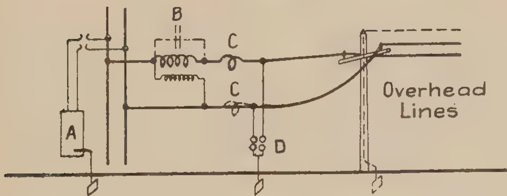


Fig. 262

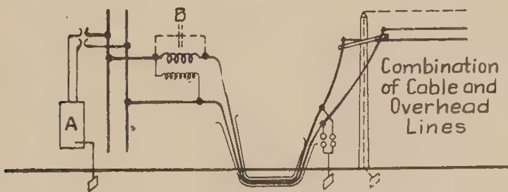


Fig. 263

Figs. 261 to 263

Line and Feeder Regulator Protection Against Excessive Voltages and High Frequencies (Single-Phase Circuits)

to frequent disturbances, particularly lightning disturbances, and especially if the feeder is not protected by ground wires and if the line voltage is 6000 or more.

(5) Choke coils in the other line conductors which have no regulators in series.

For Combination Cable and Overhead Lines

NECESSARY—(1) Aluminum cell or oxide film lightning arresters on the feeder bus.

(2) Multigap arresters on each feeder at the junction of the cable and overhead line. Cases may occur in which the multigap arrester is not sufficient and the aluminum cell or oxide film arrester may be required.

ADVISABLE—(3) By-pass cells across the secondaries of the individual regulators connected in series with the feeders to shunt disturbances, due to switching and surges, around the regulator windings.

Short lengths of cable occasionally used to connect overhead systems to the station apparatus are not considered as cable systems, except where such connections are several hundred feet in length.

The connection diagrams showing the foregoing are given in Figs. 261, 262 and 263 for single-phase circuits and in Figs. 264, 265 and 266 for three-phase circuits. The protection considered necessary for all conditions is indicated by the full lines, and the protection considered advisable for abnormal conditions is indicated by the dotted lines.

A—designates the aluminum cell or oxide film arrester on the station bus,

B—the by-pass cell,

C—the current-limiting reactor, and

D—the multigap arrester.

It is sometimes exceedingly difficult to determine whether a system is subject to excessive disturbances or not; frequently the only manifestation of such a condition is the breakdown of the regulator. Furthermore, the breakdown of the insulation is usually not due to any one

disturbance except lightning or short circuits, but is due to a series of intermittent discharges of high voltage. These intermittent discharges may, however, have so small a

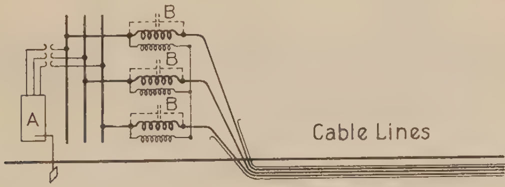


Fig. 264

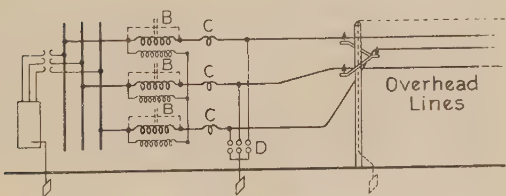


Fig. 265

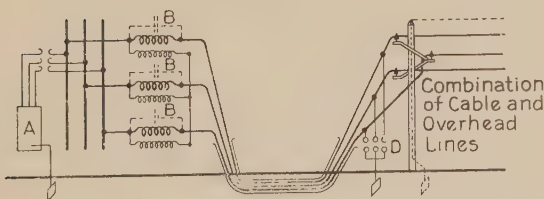


Fig. 266

Figs. 264 to 266

Line and Feeder Regulator Protection Against Excessive Voltages and High Frequencies (Three-Phase Circuits)

current capacity as not to cause a short circuit; but the discharges, if continued, finally disintegrate or carbonize the insulation at some point in the series winding so as to cause a local short circuit of high resistance which even-

tually burns out a section of the winding and so short-circuits the regulator. A regulator may therefore be in service a considerable length of time, possibly several months or even several years, before trouble develops.

Fig. 267
Short Length of Wire from Regulator Coil Subjected to Intermittent High Voltage Discharges (Enlarged to About Four Times Normal Size)

Such trouble is usually indicated by a very perceptible increase in the temperature of the apparatus without any apparent reason.

Fig. 267 is an enlarged view of a short length of conductor taken from the series winding of a regulator. The illustration clearly shows the effect of a series of discharges. The trouble was discovered by the heating of the regulator before the windings were actually short-circuited. The insulation between several turns had, however, carbonized to such an extent as to cause a local current which produced a sufficiently high temperature to indicate that there was some defect in the apparatus, this being the reason for its removal, examination and repair.

Arcing grounds (especially the arcing over of insulators in high-tension lines feeding a low-tension system), switching, and the charging of aluminum cell arresters without charging resistance constitute sources of this trouble.

The by-pass cell recommended consists of a small aluminum cell arrester with a fuse and with an air gap in series. This arrester was developed for this particular purpose about 1906, by E. E. F. Creighton. It is not extensively used because conditions only infrequently

demand this type of protection, but where required and installed, it has proved exceedingly satisfactory.

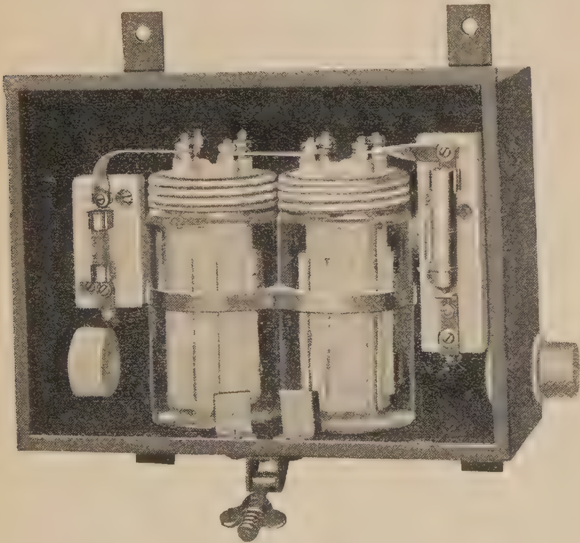


Fig. 268
By-Pass Arrester for Single-Phase Regulator Protection

Fig. 268 shows a by-pass cell for a single-phase regulator; Fig. 269 gives general dimensions, and Fig. 270 shows the diagram of connections.

Excessive Current in Feeders Under Short Circuit

As the kv-a. capacity of the distributing station increases, short circuits on the individual feeders emanating from it become correspondingly more destructive unless means are provided to limit the short-circuit current to a reasonable value, and the smaller the kv-a. capacity of a feeder with respect to the kv-a. in generator capacity, the greater is the danger.

Apparatus connected in series with a feeder under short circuit is obviously more liable to injury than appa-

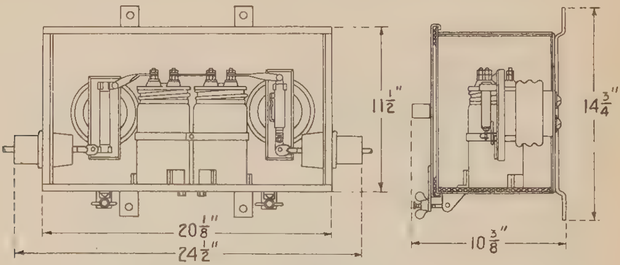


Fig. 269
Dimensions and Assembly of By-Pass Arrester for Single-Phase 2300-Volt Regulator

ratus connected across the feeder, or the feeder itself. The former usually consists of an oil switch, a current

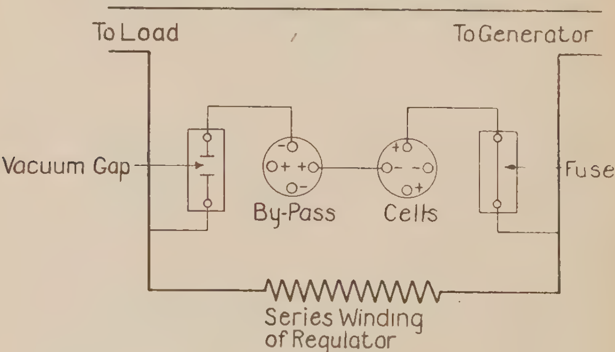


Fig. 270
Connections of By-Pass Arrester with Single-Phase Regulator

transformer, a feeder regulator, and, occasionally, a current-limiting reactor.

In modern stations, the feeder switches installed are much larger than required to break the current of the

feeder itself. The size of the switch is usually based on the maximum current it may be required to break in case of a short circuit on the feeder, the short-circuit current being determined from the total kv-a. capacity of the connected generators. Furthermore, the switches are usually installed in individual compartments or cells.

Current transformers and current-limiting reactors are usually not oil-immersed; and, due to their simple design they can readily be built to withstand very heavy overloads momentarily.

The feeder regulator is, however, a slot-wound machine and it is usually oil-immersed. It is therefore more liable to injury both mechanically and electrically, and more likely to cause damage to the station, than any other apparatus. As the regulator is a transforming device, its kv-a. capacity is a very appreciable percentage of that of the feeder regulated compared with the current transformer or the current-limiting reactor, and as it is also a costly device, it is impracticable to design it with the same factor of safety as is feasible with the other series devices. The likelihood of trouble with the regulator due to line short circuits increases rapidly with the value of the short-circuit current. The short-circuit current must therefore be limited, for it can be limited—and at small cost—by properly designed current-limiting reactors.

Short-circuit currents in the regulator windings in excess of from 20 to 25 times normal value may cause damage for any of the following reasons:

The excessive torque between the stator and rotor cores may damage the mechanism.

The mechanical stresses in the windings may displace the coils and damage the insulation, and cause short circuits within the regulator.

The short-circuit current may cause voltage stresses sufficiently high to break down the insulation and cause short circuits within the regulator.

The short-circuit current may so overheat the windings and so burn the insulation as to cause short circuits within the regulator.

Short circuits within the regulator may cause an explosion.

The extent of the damage due to a short circuit is determined to a considerable extent by the relation of the regulator to the rest of the system.

As this relation of a feeder regulator to a generating or a distributing system does not seem to be generally appreciated, an analysis of the situation should be of interest.

The Relation of a Feeder Regulator to the Generating and Distributing System

The following typical cases will be considered:

First. A feeder, controlled by a regulator, fed directly from a bus of practically unlimited power.

Second. A feeder, controlled by a regulator, supplied by a single transformer having a kv-a. capacity corresponding to the load.

The first case applies to substations from which a large number of feeders, controlled by regulators, are supplied. This is the arrangement in general use, and it will therefore be considered in detail.

The Short-Circuit Current Value

The short-circuit current is always equal to the voltage of the generator divided by the total impedance in the circuit between the generator and the short circuit. As the voltages of the generator, the transmission line, and the feeder short-circuited may, however, have different numeri-

cal values, it is preferable to consider the impedance of each part of the circuit separately and in per cent of the voltage of the unit considered. Furthermore, as the kv-a. capacities of these three units constituting a system may also have different numerical values, it is necessary to consider the individual impedance of each unit in its proportional relation to the short-circuited feeder.

As an illustration, the following installation will be considered: a 10,000 kv-a. generator having an impedance of 10 per cent; a 5000 kv-a. step-up transformer, a transmission line, and a stepdown transformer having a combined impedance of 10 per cent; and a 200 kv-a. feeder directly connected to the bus supplied by the step-down transformer.

The kv-a. capacity of the feeder is 1/50 of the kv-a. capacity of the generator. The effective impedance of the generator with respect to the feeder is therefore 1/50 of 10 per cent or 0.2 per cent. The kv-a. capacity of the feeder is 1/25 that of the transformer supplying it. The effective impedance of the transmission line including the two transformers is therefore 1/25 of 10 per cent or 0.4 per cent. The value of a short-circuit current in the feeder will be equal, therefore, to its voltage in per cent; that is, 100 divided by 0.2 per cent plus 0.4 per cent plus the impedance of the feeder itself from the transformer terminals to the short circuit, also expressed in per cent. If the feeder is controlled by an induction voltage regulator, the impedance of the regulator in per cent of the feeder voltage must be included with that of the feeder.

The average impedance of the induction type of regulator is approximately 20 per cent of its secondary or induced voltage. If the regulator has a range of 10 per cent

boost or lower, its impedance with normal current flowing is therefore 2.0 per cent of the feeder voltage.

The normal magnetizing current of the average induction regulator is about 25 per cent of its full-load current; that is, with normal voltage applied to either the shunt or series winding of the regulator, about 25 per cent of the full-load current flows through the winding connected. As the excitation voltage is increased, the exciting current increases in a much greater degree; that is, the higher the excitation of the regulator core, the smaller is the effective value of the core in limiting the exciting current.

Under short-circuit conditions, practically full line voltage (that is, ten times normal voltage) is applied to the secondary winding of the regulator, and under this condition, the short-circuit current may be considered as the exciting current. Under this extreme voltage, the impedance of the regulator is therefore considerably less than normal; that is, instead of being 2.0 per cent, it is probably less than 1.0 per cent.

If a short circuit on the feeder be now considered as existing immediately outside of the station or sufficiently near the station so that the impedance of the feeder is negligible, the total effective impedance in the circuit to limit the short-circuit current is $0.2+0.4+1.0=1.6$ per cent. As the line voltage is 100 per cent, the short-circuit current is therefore 62.5 times the normal line current of the feeder under consideration.

With the given generating and distributing system, the value of the current due to a short circuit on the feeder is therefore determined to a greater extent by the regulator than by the generating or distributing apparatus. That is, without a current-limiting reactor in the feeder,

the feeder regulator controls or determines the short-circuit current.

It might therefore seem desirable to increase the reactance of the regulator; but, as already indicated, the reactance decreases under the short-circuit conditions, so that the impedance of the regulator under normal load conditions would be prohibitive, especially with low power-factor loads. It is therefore evident that the only feasible current-limiting device is an air-core reactor.

Regulators having the same impedance drop in per cent will determine the short-circuit current according to the range of voltage control for which the regulator is designed. On the basis assumed, a 5 per cent regulator will add only 0.5 per cent to the impedance of the circuit; whereas, a 20 per cent regulator will add 2.0 per cent, and so on, the short-circuit current depending on the summation of all of the reactances in the circuit.

Stresses in the Regulator Under Short-Circuit Conditions

The 10 per cent regulator considered has a kv-a. capacity equal to 10 per cent that of the feeder, or 20 kv-a. With the short circuit assumed, it is therefore subjected to a current load equal to 62.5 times normal, and as the voltage is 10 times normal, to a kv-a. load of 12,500, or 625 times normal. Under this condition, the regulator is liable to damage: to the operating mechanism or the windings and possibly (due to a short circuit of the windings) to the tank.

Torque Stresses

The normal torque of a regulator is identical to that of an induction motor of the same kv-a. rating and wound with the same number of poles. This torque is also normally proportional to the square of the current flowing in the

series winding. However, due to the over-saturation of the core caused by the application of practically full line voltage across the series winding under short-circuit conditions, the torque, because of magnetic leakage and the voltage drop in the windings, is proportional to only about 3.5 times the short-circuit current instead of being proportional to the square of this current. The torque also depends on the relative position of the rotor to the stator, that is, on the position of the segment, the figures given being the maximum. (See Figs. 40 to 43 inclusive.)

The 20 kv-a. regulator, under the condition considered, may therefore theoretically develop a torque corresponding to 4360 kv-a. or 218 times normal. This excessive stress may break the gearing or mechanism, or it may spring the shaft of the regulator.

The mechanical design of the regulators is such that they will withstand from 75 to 100 times normal torque (corresponding to from about 20 to 25 times normal current), and it would therefore seem more desirable to limit the short-circuit current to a safe value than to attempt to design the regulators themselves to withstand the maximum short-circuit stress.

Mechanical Stresses Between Windings

The repulsion between the primary and secondary windings of both single-phase and polyphase regulators and between the phase windings of both the rotor and the stator of a polyphase regulator outside of the core is proportional to the product of the ampere-turns of the two windings; that is, approximately proportional to the square of the short-circuit current flowing. In the case considered, the repulsion between coils carrying current in opposite directions is therefore 3900 times normal. This excessive force spreads the coils and distorts them.

especially in the case of small high-voltage regulators, for in them the coils are comparatively weak mechanically due to the small section of the copper used for the windings and due to the large amount of insulation around the conductors and between the layers of the windings.

Voltage Stresses

Under short-circuit conditions, with practically ten times normal voltage impressed on the series winding of the regulator, an exceedingly high and distorted voltage is induced in the shunt winding. This high voltage may break down the insulation. The danger of a short circuit in the regulator is increased by the fact that under short-circuit conditions the windings are simultaneously stressed by the mechanical forces, and the insulation is also weakened by the heat generated by the short-circuit current, the heat varying as the square of the current.

If the regulator has so far escaped injury, it is, however still in danger of breaking down as a result of the opening of the short circuit. Energy is stored in the circuit due to the fact that the current flowing creates a magnetic field both in the inductive apparatus connected and in the line. This energy in dissipating tends to break down the insulation when the circuit is opened. Before the circuit is opened, the energy is equal to the current times the voltage. At the instant the circuit is opened, the stored electromagnetic energy is converted into electrostatic energy and the resultant voltage E is equal to the current I flowing at the instant the circuit is opened times the square root of (the inductance L of the circuit in henries divided by the electrostatic capacity C of the circuit in farads); that is,

$$E = I\sqrt{\frac{L}{C}}$$

The value $\sqrt{\frac{L}{C}}$ is designated as the surge impedance of the circuit.

From the formula, it will be observed that the higher the short-circuit current, the greater will be the tendency for the insulation to break down when the short circuit is opened.

The current value on which the preceding is based is the instantaneous current value, that is, the current value at the instant the circuit is opened. The breakdown voltage may therefore vary from zero to a maximum value depending on what point in the cycle the circuit is opened.

Heating of Windings

During a short circuit, the heat generated in the conductor must be assumed to be entirely absorbed or taken up by the conductor with a resulting increase in its temperature. Fig. 271 shows the relation between the short-circuit current in a standard 36 kv-a. regulator and the time required for the current to melt the conductor. A severe short circuit may therefore be opened in the regulator itself unless the circuit breaker is adjusted for instantaneous opening.

Explosions

If a line short circuit is sufficiently severe to cause a break or open circuit in the winding or a short circuit inside of the regulator and if the short circuit is maintained, the heat generated by the arc will vaporize the oil and an explosion may result. Such occurrences have fortunately been rather unusual in the past, but must be expected more frequently as the kv-a. capacity of generating stations and substations is increased, unless some means is taken to limit the short-circuit current to a reasonable amount.

The danger of explosions is greater in the smaller units for the reason that the smaller the regulator and the larger the source of supply, the greater will be the short-circuit

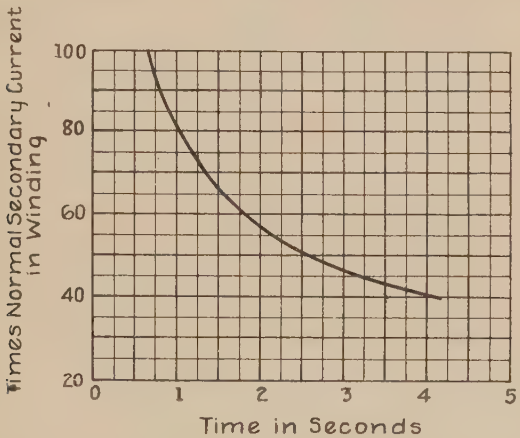


Fig. 271

Time Required to Melt Copper in Secondary of Single-Phase Regulator at Various Current Densities

current with respect to the normal current of the regulator short-circuited.

An explosion may be caused by the rapid generation of gas due to an arc under the oil or by the ignition of a mixture of gas and the air in the tank above the oil. With an arc under oil, it is doubtful whether any diaphragm or vent smaller than the full opening of the tank will be protective, and still more doubtful if the proper mixture of gas and air is ignited. The danger in an accident of this kind is in the flooding of the station with oil which may catch fire.

In considering the danger of explosions it might seem that it would be safer to use a corrugated sheet iron tank

instead of a cast iron one, but experience has shown that sheet iron tanks are as likely to be ruptured as the cast iron units.

The danger of explosions also exists in oil switches and oil-immersed transformers, and similar accidents have been experienced with them. The danger is not, however, so great in either the switch or the transformer as in the regulator. When switches are installed, the design and size recommended does not so much depend on the circuit to be controlled as on the kv-a. capacity of the connected generating units, whereas transformers are connected in shunt to the line and have a relatively high impedance so that they are to a certain degree self-protecting.

It is therefore evident that, as the regulator cannot be economically designed so that it is self-protecting, it is necessary to limit the short-circuit current to a safe and reasonable value.

It may be of interest to note in this connection, that the by-pass cell, recommended for the protection of the regulator against voltage surges, may under short-circuit conditions become a source of added trouble. The voltage for which the by-pass cell is designed is equal to the secondary or induced voltage of the regulator. Subjecting the cell to ten times normal voltage, as in the case of a short circuit, may cause an explosion in the cell similar to that which occurs in the regulator under similar conditions.

The second case in which the distributing transformer has a kv-a. capacity corresponding to the load on the feeder, may be considered in the same manner as the first. However, in this case, the entire reactance of the step-down transformer is added directly to that of the regulator, which reactance combined with the percentage of the reactance of the transmission line and the generator in the

ratio of their kv-a. capacities will limit the short-circuit current to a safe value.

As the short circuit may happen anywhere on the feeder, the short-circuit current will vary depending on the impedance of that part of the line included in the short circuit. To find the value of the short-circuit current under this condition, the value of the impedance of that part of the feeder included in the short circuit should be added to the regulator impedance.

It may be of interest to note that, for a line of a given length and section of copper, the short-circuit current on a cable is considerable greater than on an overhead line because the reactance of a cable is only about 40 per cent that of the overhead feeder. The impedance of the feeder usually represents the only protection against damage due to line short circuits, so that an overhead line offers relatively more protection to the regulator than the cable.

Polyphase regulators of comparatively small kv-a. capacities wound for high voltages are more subject to damage in the windings than those wound for the lower voltages because of the flexibility of windings built up of small conductors and the difficulty of adequately bracing them. The coils of the larger polyphase regulators, regardless of the voltage for which they are wound, and those for all single-phase regulators are, however, much more rigid and substantial and, hence, can be much better supported.

The torque of the polyphase regulator is greater than in the single-phase design of a corresponding kv-a. capacity. Because of the smaller torque in the single-phase regulator and also because its coils are much more rigid (see Figs. 25 and 26), this design will therefore safely withstand higher short-circuit currents than the polyphase regulator.

A current of 25 times normal, limited to this value by a 3 per cent current-limiting reactance, has been considered safe for practically all conditions of operation.

Protective Devices

As previously stated, the relation of the regulator to the line with regard to line disturbance has, in general, not been realized; but, from the foregoing, the importance of providing some protection for the regulator must be appreciated. Nearly all stations have aluminum cell lightning arresters on the bus, but many have no protection whatever on the regulator. In such cases, line disturbances must pass through the regulator winding which, acting as a choke coil, reflects the charge back into the line at practically double voltage, delaying and reducing the action of the arrester; that is, the regulator protects the rest of the station apparatus, and, not being designed for this purpose, trouble results.

As has also been previously stated, the insulation between turns and layers of regulator windings is designed so as to have an exceedingly high safety factor when compared with the normal induced voltage. Sufficient insulation is provided so that, in the case of surges, the breakdown is as likely to occur to ground as between turns and layers. This arrangement of insulation affords ample protection for all ordinary operating conditions but will not withstand the high-voltage surges to which some systems or feeders may be subjected. For such cases, adequate and ample protection must therefore be provided external to the regulator.

In considering the various designs of protective devices available, it must be appreciated that, while undoubtedly any design of lightning arrester or choke coil protects the circuit to a greater or less degree, the maximum protection

and insurance against trouble is obtained by using apparatus which is of the highest quality and best suited to the circuit it is intended to protect, and by properly installing such apparatus and keeping it in good condition. The choke coils should have sufficient reactance to reflect detrimental disturbances, and the time constant of the arresters should be such as to ground the disturbance before it can damage the installation. The aluminum cell arresters should be provided with charging resistances, for, otherwise, the charging of the cells may introduce surges similar to arcing grounds or short circuits. The by-pass cells should be connected across the secondary of the regulator as close to the regulator as possible, and all ground wires should be of ample section and of minimum impedance. Furthermore, although protective devices perform no useful function in the normal operation of a system, yet, to be effective in case of trouble they must be given the same care, inspection, and attention as any other electrical apparatus.

Recommendations

All regulators should be protected against high voltages for the same reasons that other electrical apparatus of similar design and character is protected.

An aluminum cell or oxide film arrester should always be connected to the station bus.

Overhead lines should always be protected by lightning arresters at their entrance to the station.

The junctions of overhead and underground lines should always be protected by an arrester.

All regulators controlling feeders which are subjected to abnormal voltages should be protected by choke coils and by by-pass cells.

All regulators controlling feeders which are subjected to short circuits in excess of from 20 to 25 times normal current should be protected by current-limiting reactors of the air-core type.

There is a decided advantage in the use of current-limiting reactors, for by their use the size and cost of feeder switches may be reduced. The design of the switches need not then be based on the kv-a. capacity of the generators connected, but only on the maximum possible short-circuit current on the feeder controlled. The use of the reactance will, however, require a regulator of greater range in order to compensate for the voltage drop in the reactance. The over voltage required of the regulator will depend on the power-factor of the load. For instance, a 3 per cent reactance with full-load current flowing and with the feeder supplying an 80 per cent power-factor load will increase the line drop by 1.8 per cent. The current-limiting reactor therefore increases the initial and operating costs of an installation; but, if feeders are subject to short circuits, it will reduce or eliminate losses incident to line short circuit, and preserve the continuity of service so essential to public service corporations.

SECTION XXVII

VOLTAGE REGULATION BY MEANS OF THE INDUCTION REGULATOR COMPARED WITH OTHER MEANS OF REGULATION

Practically all feeder voltage regulation is obtained by the use of induction regulators, but conditions sometimes occur which may be better satisfied by some other means of voltage control. Aside from the induction regulator, the principal means used for obtaining voltage regulation on feeders are:

- Transformers arranged with taps in the winding;
- Transformers with taps and dial switches, and an induction regulator;
- Synchronous boosters;
- Synchronous condensers;
- Static condensers.

The advantages and limitations of each of the methods are briefly as follows:

Transformers with Taps

Transformers arranged with taps intended for voltage regulation are usually provided with a dial or some other step-by-step switch, or combination of switches, to facilitate the changes in the connections of the windings. The variable part of the winding may be a part of either the primary or secondary winding of the transformer, depending on the voltage and current to be handled. With this method of regulation, the turns of the windings not used are cut out of circuit, and the copper loss is thereby reduced. This makes the method highly efficient, especially if a considerable range of voltage control is desired. For the

latter condition, it is generally preferable, if it is feasible to do so, to make the secondary winding the variable one, for, if the exciting winding is variable, the core loss and the exciting current of the transformer are also variable over a wide range due to the change in the number of primary turns. The range of voltage control for a given winding may be increased by having one section reversible, thus giving a total voltage range equal to twice the voltage of the reversible section. If the voltage of the entire output of the transformer is to be regulated, the variable portion of the winding forms part of the main winding of the transformer; but, if only a portion of the load is to be regulated, a smaller transformer unit may be used, the secondary of which is variable and reversible. This auxiliary transformer is connected in series with that portion of the load requiring regulation. Such a regulating transformer is designated as a switch type of regulator, and a number of designs and sizes have been built both for hand and for automatic operation.

If the voltage requires only infrequent adjustment and the circuit can be opened while the adjustment is being made, the least expensive arrangement is to provide the transformer with taps, but without a switch; changing the line connection as conditions may require. The next best arrangement is to provide interconnected knife-blade switches or a pivot switch. If, however, the voltage is to be changed under load, a more elaborate switching mechanism is required. Such a switch must be arranged with double blades insulated from each other but connected through a reactance or a resistance which reactance or resistance bridges the taps while the line connections are being changed.

This method of regulation can be used directly in higher voltage circuits than any other method of control, regulating switches having been built for 25,000-volt circuits. Such switches have also been built to control 800-amp. circuits, but the cost of the equipment increases rapidly with an increase in the voltage and the current to be handled.

A number of designs of switching arrangements have been developed for various requirements and used to some extent. Figs. 272 to 277 inclusive show some of the principal arrangements.

Fig. 272 shows a motor-operated dial switch for moderate currents and voltages. Fig. 273 shows a straight line switch electrically equivalent to that shown in Fig. 272. Fig. 274 shows a series of electrically operated and electrically interconnected contactors. Fig. 275 shows a motor-operated mechanically interconnected arrangement of oil switches. Fig. 276 shows a self-contained regulating transformer with a reversible dial switch. This latter arrangement is designated as the switch type of regulator. Fig. 277 shows the automatically operated switch type of regulator removed from its tank. The switch type of regulator shown in Figs. 276 and 277 is usually limited to currents not exceeding 200 amperes, and to voltages not exceeding 2500.

The voltage regulation obtainable by changing winding tap connections is necessarily in steps depending on the number of transformer taps and the voltage between taps. If the requirements demand a smooth regulation over a considerable voltage range, and if the load to be regulated is considerable, a compromise may be made by combining a transformer with taps and switches with an induction regulator, the regulator being used only to obtain a gradual voltage change between the transformer taps.

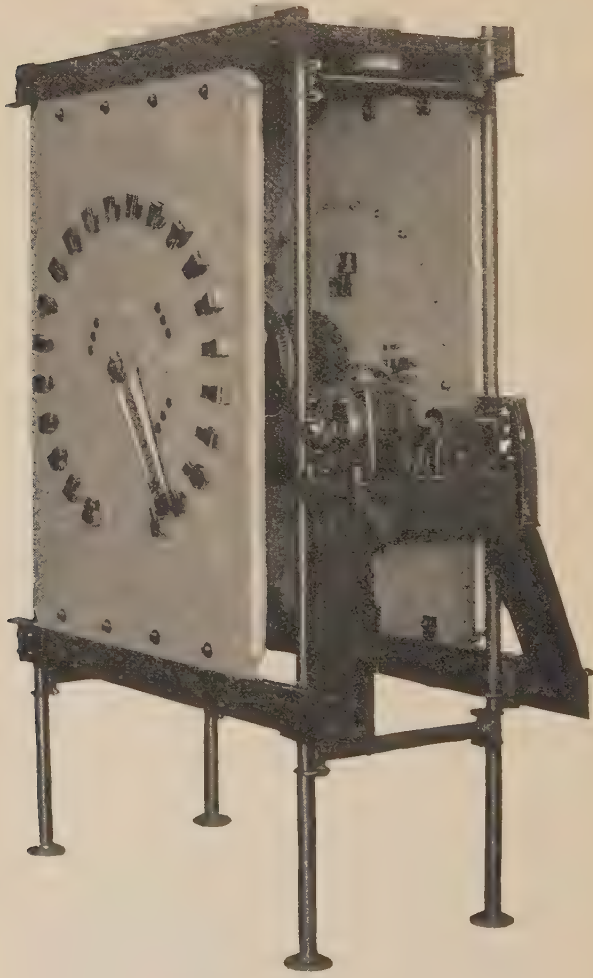


Fig. 272
43-Point Dial Switch

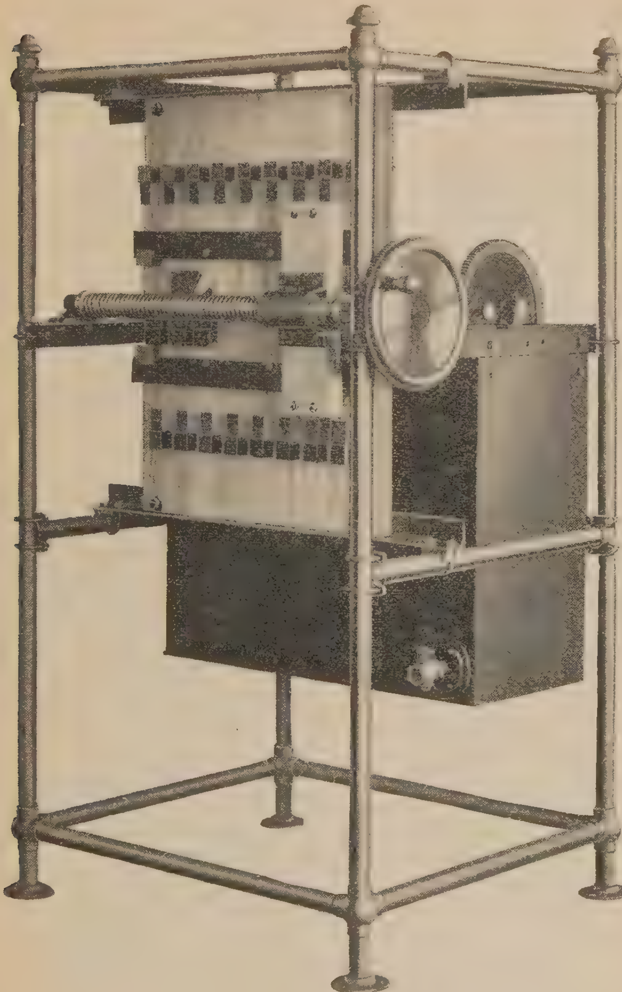


Fig. 273
17-Point Straight Line Switch

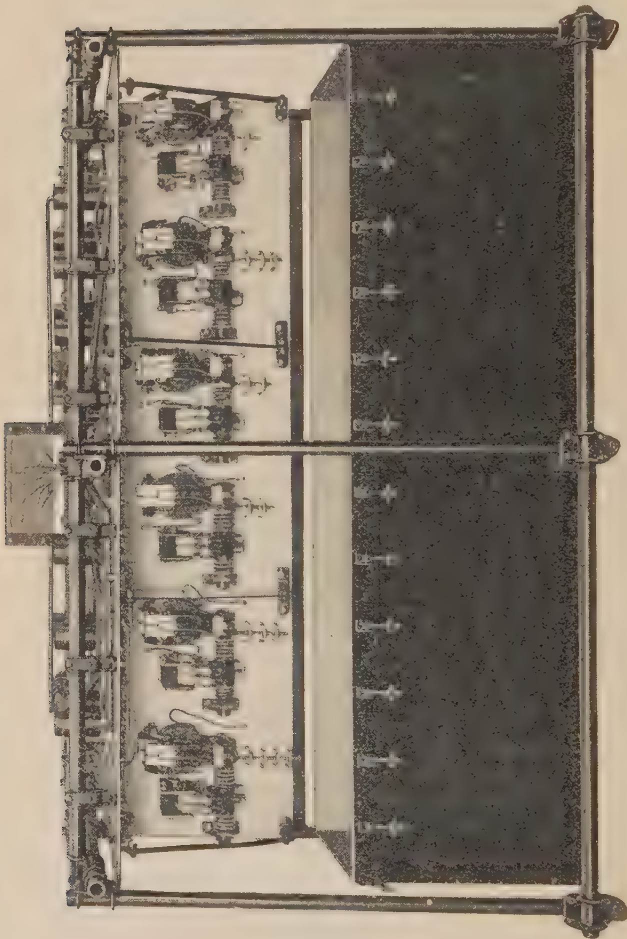


Fig. 274
Panel for Use on 600 Kw. Transformer to Open 500-Amp., 2300 Volts on the Intermediate Taps

The advantages of the switch method of voltage regulation are the high efficiency with regard to losses, and the low cost.

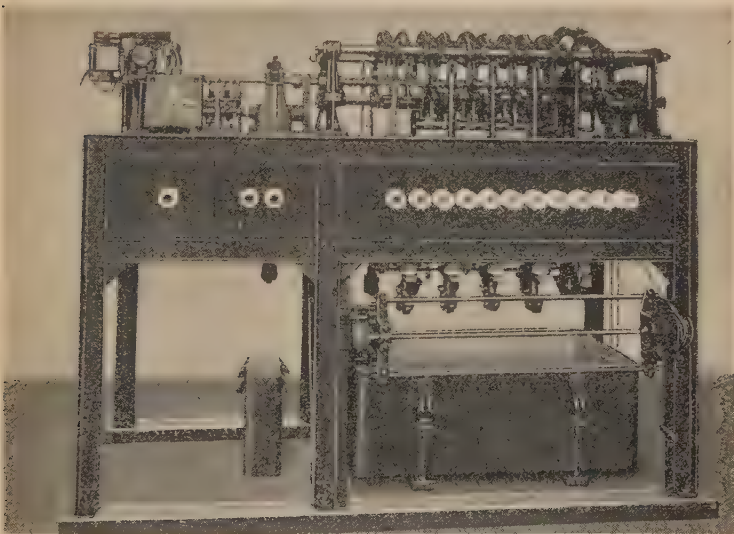


Fig. 275
Motor-Operated Circuit Breaker for Changing Transformer Taps (Oil Tank Lowered)

The disadvantages are that the voltage range is produced in steps depending on the number of transformer taps, the inadvisability of operating a regulating switch controlling a large amount of power, and the general disadvantages of switching either high-voltage or high-current circuits.

Transformer with Taps and Dial Switch, and an Induction Regulator

The advantages of the switch method of regulation can be obtained and the disadvantage can, to some extent,

be eliminated by the use of an induction regulator so arranged as to produce a gradual voltage change between the successive transformer taps.

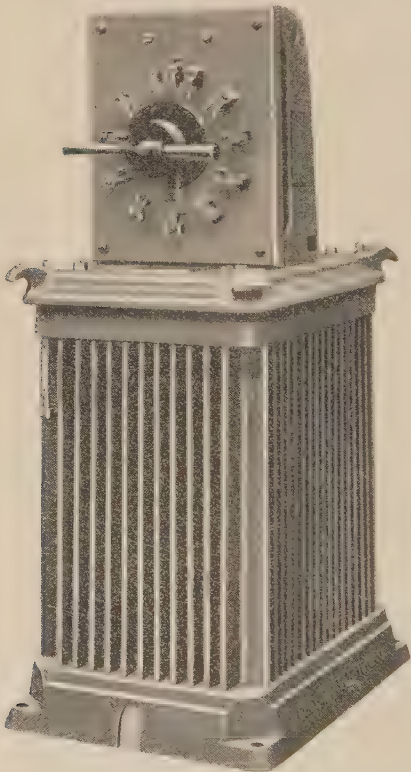


Fig. 276
Regulating Transformer

This method is particularly adapted to conditions requiring a very considerable range in voltage such as required by certain classes of furnaces. The connections, design, and operation are briefly as follows:

If an auto-transformer be connected across a supply circuit and a 50 per cent tap be brought out of the windings, then one-half of the supply voltage is obtainable between the auto-transformer tap and either of the winding terminals. In Fig. 278, the auto-transformer is connected across taps *5* and *6* of the primary of the transformer winding. The tap *T* brought out at the center of the auto-transformer winding therefore has the same voltage with reference

to taps *5* and *6* as the center of that part of the main winding of the transformer between these taps, that is, as the point *a*. If, however, either side of the auto transformer be disconnected from tap *5* or *6*, the entire current is forced through that half of the auto-transformer winding still connected and this winding now becomes a reactance in series with the line. Breaking either of the connections lowers the tap voltage and causes arcing on the switch contact while the circuit is being opened, depending on the current and voltage broken. It is for this reason that dial or tap switches, handling any appreciable current or voltage and provided with an auxiliary resistance or reactance, are arranged so that the current is made and broken by means of an auxiliary contactor or oil switch rather than by means of the dial switches themselves.

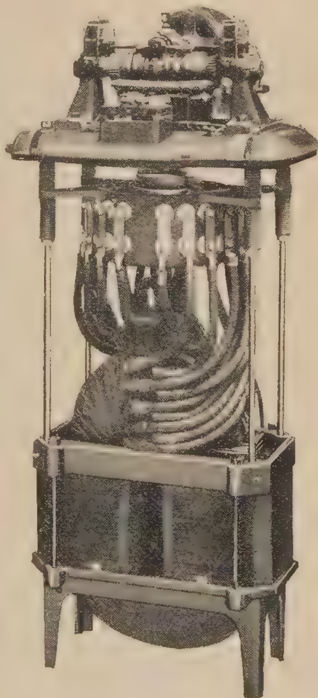


Fig. 277
Feeder Potential Regulator

Instead of connecting an auto-transformer across the taps of the main transformer, a transformer with separate

primary and secondary windings (but having a 50 per cent tap brought out of the secondary winding) may be so connected, as shown in Fig. 279. With the primary of this

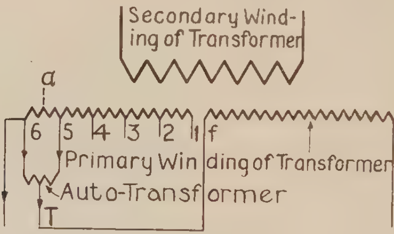


Fig. 278
Connection of Auto Transformer Across Taps of Main Transformer

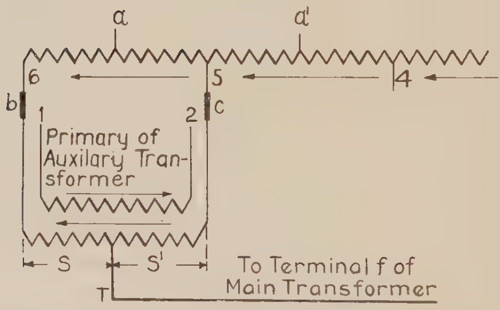


Fig. 279
Connection of Transformer Across Taps of Main Transformer

transformer open, the arrangement is identical to Fig. 278, but it is evident that the voltage relations may be changed by exciting the primary of this auxiliary transformer.

If the primary winding of the auxiliary transformer be excited so that the voltage of its secondary be just equal and opposite to the voltage between taps *5* and *6* (that is in direction of the arrows in Fig. 279), it is evident that the

same voltage conditions would still prevail as in Fig. 278, and that the tap T could be directly connected to point a on the main transformer winding. In the present case, however, either end of the secondary winding of the auxiliary transformer may be disconnected from the main transformer by the switches b or c without causing an appreciable arc and without any voltage disturbances, for the reason that the voltage of the tap T remains fixed and equal to the voltage of point a on the main transformer winding because the voltage in the secondary of the auxiliary transformer is now supplied by a separate primary winding.

The change in the voltage across the secondary winding of the main transformer is obtained by changing the connections of the auxiliary transformer to successive taps in the primary winding of the main transformer and by gradually varying and reversing the excitation of the primary of the auxiliary transformer.

The cycle of operations and the results obtained are as follows: With both ends of the auxiliary transformer connected to adjacent taps as shown in Fig. 279, and with the primary of the auxiliary transformer excited so that the voltage across its secondary winding is equal but opposite to the voltage across the taps of the main transformer to which it is connected, switch b may be opened. The winding of the main transformer between taps 6 and 5 is now inactive; but the voltage of the secondary of the main transformer remains as before, for the voltage on tap T and point a are still identical even with full-load current flowing. That is, one-half of the auxiliary transformer, S', is now, in effect, in series with the line but boosting, so that the voltage at tap 5 is still equal to that which it would have been had the line been connected to

point *a*. By now varying the voltage of the primary of the auxiliary transformer, the voltage at tap *5* may be varied. Reducing the primary voltage of the auxiliary also reduces

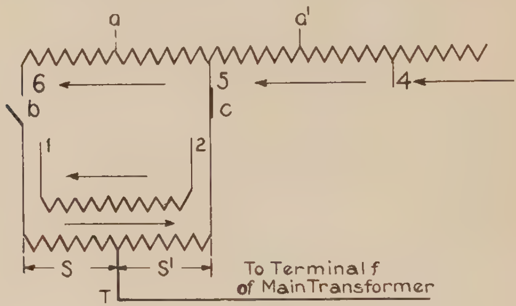


Fig. 280

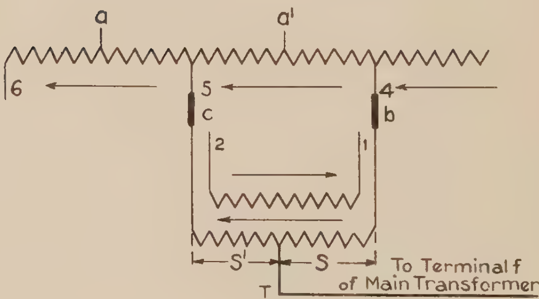


Fig. 281

Figs. 280 and 281

Analysis of Action of Auxiliary Transformer Connected Across Taps of Main Transformer with the Primary Voltage of the Auxiliary Transformer Variable

the voltage of the secondary S'. With zero voltage on S', the line voltage is in effect applied directly to tap *5*, and the secondary voltage of the main transformer is correspondingly decreased. If, now, the voltage of the auxiliary transformer be again increased, but in the opposite direc-

tion, the secondary voltage of the auxiliary will be correspondingly changed. This condition is shown in Fig. 280 and is indicated by the change in the direction of the arrows showing the direction of the voltage. As the auxiliary transformer has been reversed electrically, it may now also be reversed mechanically as shown in Fig. 281. That is, connection *c* of the auxiliary remains on tap *5*, and connection *b* may now be connected to tap *4*. Fig. 281 is identical to Fig. 280 with regard to the direction of the voltages, for only the mechanical position of the auxiliary with respect to the main transformer is changed.

In other words, by again adjusting the voltage of the auxiliary until its secondary voltage is exactly equal to the voltage between taps *5* and *4*, it can then again be connected at both ends as shown. The voltage at tap *T* now corresponds to the voltage at point a', on the main transformer winding. Either tap *5* or tap *4* may now be disconnected and the cycle repeated or reversed as desired.

By continuing the process of consecutively spanning the successive taps and by varying the voltage of the auxiliary as described, a uniform and gradual change is produced in the voltage of the secondary of the main transformer.

The primary voltage of the auxiliary transformer is most conveniently varied and reversed by means of an induction regulator; in fact, the auxiliary transformer can be entirely replaced by a regulator, for the secondary of the regulator produces the voltage variations and reversals required, without a corresponding variation in its primary voltage. (See Fig. 282.) The use of a regulator alone would, however, require a double secondary winding in the regulator as indicated by the auxiliary transformer

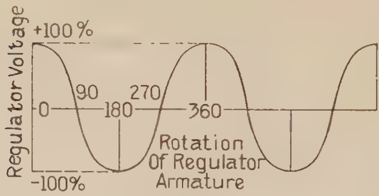


Fig. 282
Voltage Curve of a Single-Phase Induction Regulator

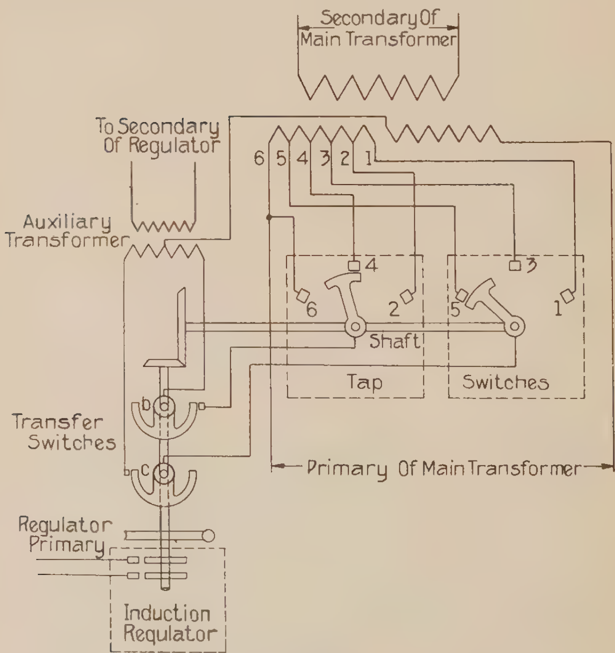


Fig. 283
Connection Diagram of Transformer with Taps; Tap and Transfer Switches; Auxiliary Transformer; and an Induction Regulator for Voltage Regulation

diagrams, and furthermore, as the main transformer may be wound for a relatively high voltage, it is advisable from a cost standpoint and for reasons of insulation, to use an auxiliary transformer as shown.

It will be noted from Fig. 278 that, if the transformer taps are brought out so that successive taps always include the same number of turns, the voltage across the taps increases as successive sections of the winding are cut out of circuit. This necessitates a varying excitation in the primary of the regulator. If, however, the regulator is excited directly from the secondary of the main transformer, the required variation in the excitation voltage is obtained automatically, for as the primary turns of the transformer are cut out and the voltage between taps increases, the secondary voltage of the transformer increases in exact proportion. If, therefore, the ratios of the auxiliary transformer and of the regulator are correct for one position or connection, these ratios will be correct for all positions. Whatever the tap connections, therefore, the transfer switches can be opened or closed without a change in voltage and without any appreciable arcing.

Attention is also called to the arrangement of the taps of the main transformer as shown in Fig. 278. The taps are in effect within the transformer winding rather than at the end of the winding. With this arrangement, the voltage across the winding does not increase as successive sections are cut out, the maximum voltage across the winding for any tap connection never exceeding the line or impressed voltage.

As a gradual voltage change can be obtained only by a definite sequence of operation of the switches and the regulator, it is desirable to connect the regulator and the switches mechanically and thus eliminate the possibility

of wrong connections which would be likely to occur if the switches and the regulator were independently operated.

Either two dial switches or a straight line switch, as shown in Figs. 272 and 273 respectively, are therefore mechanically connected to an induction regulator so that, by a continuous operation of the regulator-operating motor or handwheel, the entire voltage range or any desired part of the range can be obtained without any interruption or abrupt voltage changes in the circuit and without any possibility of wrong connections. In order entirely to eliminate the making and breaking of current by the blades or contacts of the dial or tap switches, the auxiliary or transfer switches previously mentioned are used. These auxiliary switches are in series with the dial or tap switches and are mechanically connected or geared to them so that they always close the circuit after the dial switch is closed and open the circuit before the dial switch opens. The general diagram of connections of the entire regulating equipment is shown in Fig. 283 and the construction and operation are as follows:

The regulator and switching mechanism are designed to carry the full-load current and voltage continuously so that they may be left in any position in which the desired voltage at the load is obtained.

With the arrangement described, the induction regulator is required to be rotated through several revolutions depending on the number of taps brought out of the main transformer. The primary or excitation winding is therefore brought out through collector rings instead of by means of flexible cables as in standard regulators. A complete wormwheel, instead of a segment only, is therefore required to adjust the rotor.

The regulator is operated by the usual operating motor mounted on the regulator cover, which motor also operates the dial and auxiliary switches. A limit switch is provided,

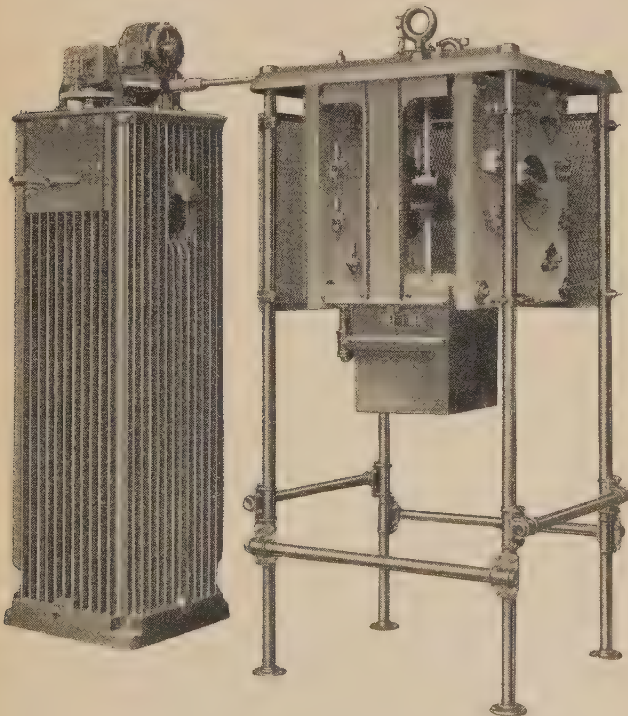


Fig. 284
Single-Phase Induction Voltage Regulator and Regulating Switch

either on the regulator or on the dial switch frame, whereby the operating motor is cut out of circuit at either limit of the voltage range of the main transformer.

The regulator shaft is geared to the shaft on which the auxiliary switches are mounted or by means of which they

are operated. These switches are arranged so that one end of the auxiliary transformer winding is always connected to a tap of the main transformer winding and also so that, when the regulator is in either its maximum boosting or lowering position, both ends of the auxiliary transformer winding are respectively connected to two consecutive taps of the main transformer winding.

The regulator and transfer switch shafts are geared to the common shaft of the two tap switches in such a ratio that the regulator shaft makes one-half revolution, that is, the regulator is operated from a maximum lowering to a maximum boosting position, or vice versa, while the blade of one tap switch passes from its central contact with a stationary switch clip to a neutral position between stationary clips or contacts. The tap switch blades therefore rotate as the regulator rotates.

In order to insure full contact while either or both blades are carrying current, both blades are of sufficient width so that one blade or the other will remain in full contact while the regulator is rotated through each successive cycle. The blades of the two tap switches are mounted on a common shaft but are offset with regard to their angular positions to each other. When one blade is in full contact in one extreme position, the other is in full contact in the other extreme position; that is, when one blade is in the center of its position, the other blade is midway between contacts. The tap connections of the main transformer are brought to the two tap switches alternately as shown, and the terminals of the auxiliary transformer are connected to the blades through the transfer switches. As each blade makes connection with only every other tap of the transformer, the successive movement of both blades therefore causes a reversal of the connection of the auxiliary trans-

former every time both terminals of this transformer are connected to the successive taps of the main transformer. This is, however, the requirement of operation as shown in Figs. 279, 280 and 281, and is the reason for the use of the two tap switches and their alternate connection.

As the regulator, tap switches, and transfer switches are connected together with gearing, and also as the switching of the auxiliary transformer connections can be made only when the regulator has its maximum voltage value (whether boosting or bucking the voltage), the opening and closing of the connections by means of the transfer switches must be made in a short interval of time; that is, while the regulator is in its maximum voltage position. Due to the fact that the voltage curve of the regulator is a sine curve (see Fig. 282), the maximum voltage value of the regulator is practically constant through a very appreciable angle of rotation of the armature. The corresponding angular rotation of the regulator shaft, during which the regulator voltage is practically constant, is sufficient to insure the operation of the transfer switches in their proper sequence, and these switches operate, as it were, in synchronism with the regulator. The actual transfers of the auxiliary transformer terminal connections to the successive taps of the main transformer winding are made by the tap switches, but the circuit is opened and closed at the proper time as required, by the transfer switches. These switches are therefore made exceptionally heavy and substantial and arranged so that the contacts can be easily renewed.

If the switches and the mechanism are properly designed, this method of control is absolutely reliable and has a much higher efficiency and a less effect on the power-factor than an induction regulator of sufficient size to give the entire range.

The operation of the regulating equipment may be by hand, by motor, or it may be automatic. If automatic, either a constant current or a constant voltage may be

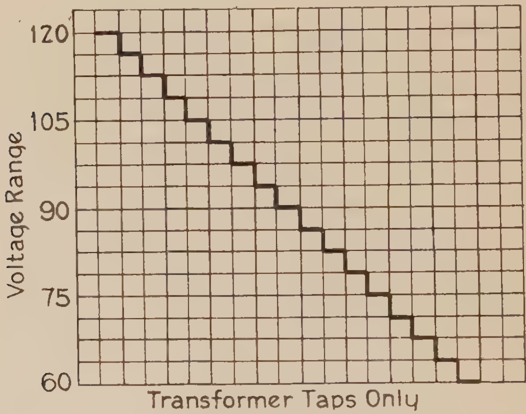


Fig. 285
Voltage Regulation Obtainable with a Tap Switch

maintained on the load but within the limits imposed by the design of the apparatus whereby the range of current or voltage is obtained and within the limits of time imposed by the time required to operate the switch.

In the smaller sizes of units, the cost of this equipment is higher than a single regulator because of the cost of the switches, mechanism, and auxiliary transformer; but, in the larger units, the cost is less. This design of voltage regulating equipment has been used in a number of installations for the control of single-phase circuits. It also is applicable to the control of polyphase circuits; but, in this case, it is necessarily more complicated and comparatively more expensive as compared with a polyphase regulator.

The arrangement described is identical to the combination of a double-dial switch or straight line switch arranged with preventive resistances or reactances and the auxiliary

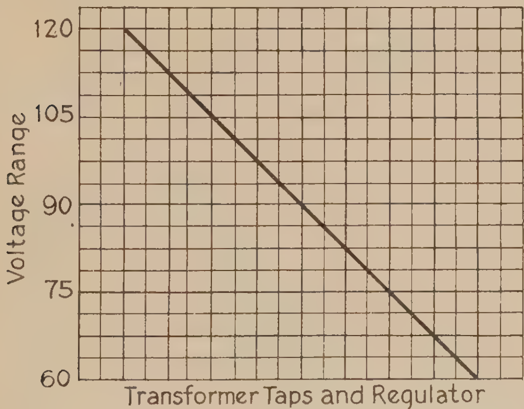


Fig. 286
Voltage Regulation Obtainable with a Combination of Tap Switch and an Induction Regulator

switches which have been used in the past (illustrated in Figs. 272 and 273 except that, in the present arrangement, an induction regulator is used in place of the preventive resistance and reactance).

Fig. 285 illustrates the voltage range obtainable with regulating switches only, and Fig. 286 shows the voltage regulation obtainable by connecting an induction regulator successively across the transformer taps and operating the combination as described.

The tap switches described and illustrated are of the double-dial type. The connections and the operation of the straight line switch are identical thereto, the only difference being in the mechanical design.

Fig. 284 shows a single-phase induction regulator, and a tap switch arranged, as described, complete with the auxiliary switches, the latter being operated under oil. The regulating equipment shown is one of several built for a corresponding number of 6000-volt 1500 kv-a. 50-cycle single-phase transformers having a range in secondary voltage of from 60 to 120 volts. The transformers were arranged with 17 taps (that is, 16 steps), and the regulators were nominally rated 47 kv-a., at the mean secondary voltage of the transformers. A regulator alone to give the same range in voltage would have been rated 500 kv-a. and the primary of the transformer would have been subjected to a voltage range of from 4000 to 8000 thereby increasing its cost and its losses. It will therefore be observed that, for conditions requiring a considerable voltage range, the combination of switches and an induction regulator is more economical, more efficient, and affects the power-factor of the circuit controlled to a less extent than an induction regulator designed to cover the entire voltage range, and that the voltage range is obtained gradually instead of in steps as obtainable by means of a dial switch only.

Synchronous Boosters

The synchronous booster is connected in series with the circuit to be regulated in the same manner as the induction regulator. The adjustment of the voltage of its series winding, and hence of the feeder regulated, is however obtained by varying the d-c. field excitation of the synchronous booster instead of by a mechanical change in the relative positions of the rotor and stator as in the induction regulator. In other words, a synchronous booster consists of an alternating-current generator connected in series

with the circuit, the voltage of which it is to control, and driven in synchronism therewith.

The synchronous booster type of regulator is used principally in connection with synchronous converters, the series booster being mounted on the same shaft and base as the converter, as shown in Fig. 287. With this arrangement, the booster can in general undoubtedly be furnished at less cost and will occupy less space than an induction regulator. The two armatures being mounted on the same shaft have their windings connected directly in series without intervening collector rings or cables. The collector rings and terminals are connected to the series booster instead of to the synchronous converter as in a standard synchronous converter. Better and more efficient ventilation can be obtained in a rotating design of regulator than in a stationary type. This allows of higher current densities in the windings, and, hence, lower costs. The direct-current exciting winding of the booster is of much simpler design than the corresponding alternating-current exciting winding of an induction regulator. This still further reduces the cost. With this arrangement, the number of poles of the booster must, however, be equal in number to the number of poles of the synchronous converter. This increases the cost.

The voltage of the series booster is both variable and reversible at will, and due to the armature reaction, is always somewhat out of phase with that of the synchronous converter except at no load. When boosting the voltage, the synchronous converter acts as the driving motor; but, when lowering the voltage, the booster acts as a motor driving the synchronous converter. This change in the direction of the torque of the regulator or series booster must be compensated for in the design of the synchronous

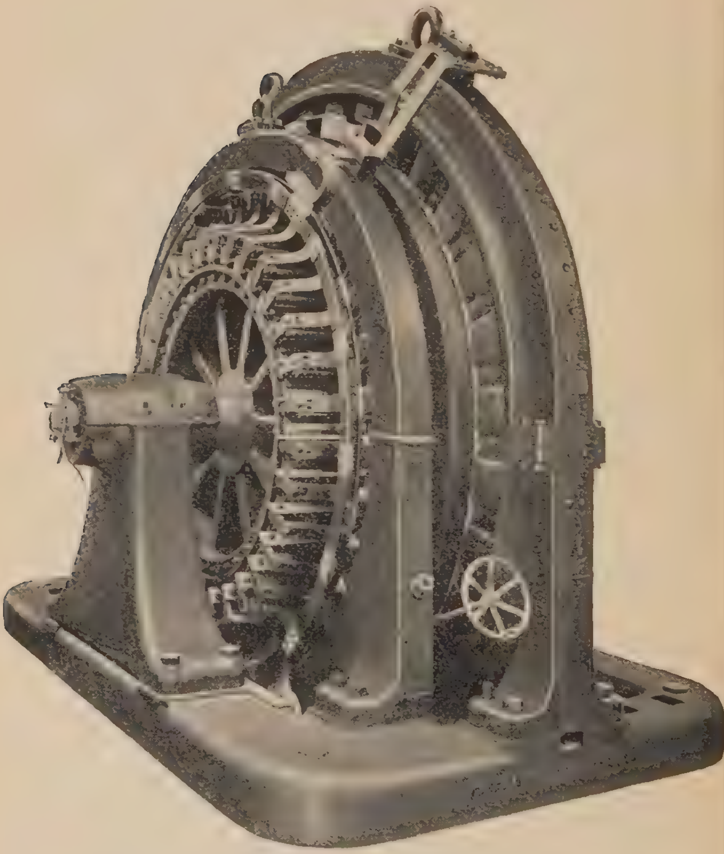


Fig. 287
32-Pole, 5800 Kw., 225 R.P.M., 580-Volt Synchronous Condenser

converter and adds somewhat to its cost; but in general, in the larger sizes, the total cost of the synchronous booster is lower than that of an induction regulator, especially for high-current machines.

In furnishing synchronous boosters for large low-speed synchronous converters, it is sometimes more economical from a cost standpoint to drive the booster by a high-speed synchronous motor, for, in general, the higher the speed of a machine, the lower its cost per kilovolt-ampere output.

Such an arrangement is illustrated in Fig. 288, the synchronous motor being of the same kv-a. capacity as the driven booster or series generator.

The synchronous motor is connected across the line to be regulated, and the synchronous booster generator is connected in series with it. Each machine is electrically independent and each has its own field excitation and regulation; but, being mechanically coupled and thus always operating in synchronism, their combined performance is similar to that of an induction regulator, as illustrated in Figs. 1 and 2.

With the series machine boosting the voltage, it acts as a generator and requires a driving power which is furnished by the synchronous motor; that is, an increase in the regulated voltage is obtained by an expenditure of current for the motor. If the series machine lowers the voltage, it absorbs power from the line, and this power must, therefore, again be delivered to the line by the synchronous motor in the form of additional current; that is, the series generator now acts as a motor and the shunt motor acts as a generator operating in parallel with the source of power. It is obvious that the booster set must and does operate in synchronism with the generator

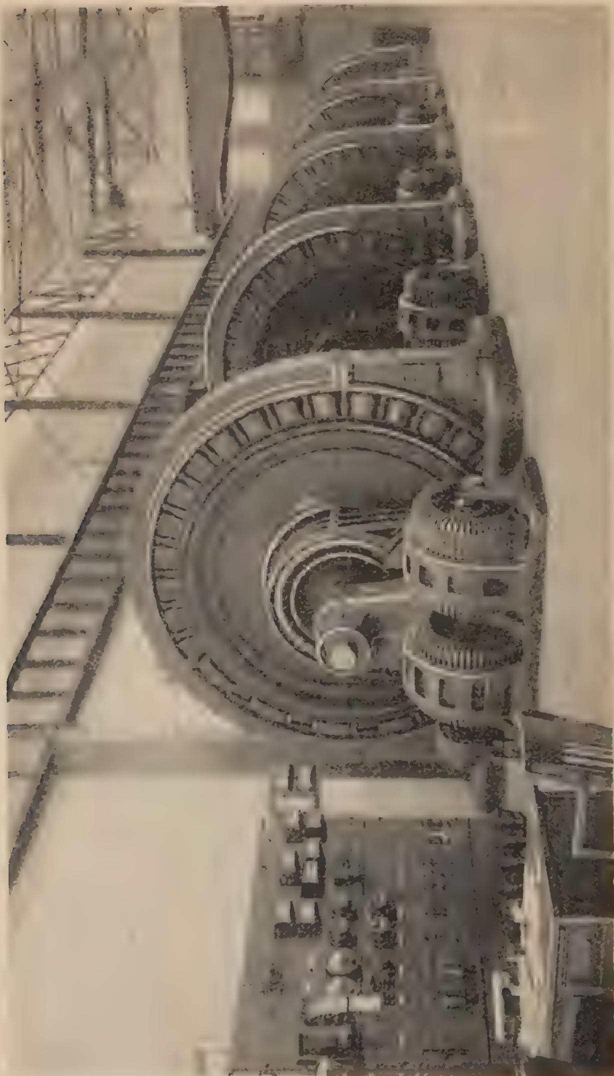


Fig. 288

Five 32-Pole, 5800 Kw., 225 R.P.M., 580-Volt Synchronous Converters of the Anaconda Copper Mining Co., Great Falls, Mont.

supplying the line or feeder regulated; but, due to the characteristics of the synchronous motor and generator the voltage of the booster is more or less out of phase with the voltage of the line except under conditions of no load.

It is generally known that the direct-current field of a synchronous machine varies in its mechanical position with reference to the rotating alternating-current field, the angle of deflection or deviation depending on the load. If the machine is operated as a motor, the motor lags; and if operated as a generator, it must be advanced. These angular displacements are determined by the design of the machine, and in the motor-generator used as a regulator, their summation determines the angular displacement of the terminal voltage of the booster with respect to the line voltage. This can be best illustrated by a diagram. Fig. 289 shows the characteristics of the motor and booster and the relation between the resultant booster voltage and the line and load voltages with the motor-generator giving its maximum boosting effect under full-load conditions.

The motor diagram can be readily constructed from the design constants of the machine, and in Fig. 289:

OE = Line voltage.

OE_M = Counter e.m.f. of the motor at no load. OE_M is practically opposite to the line voltage and practically equal to it in value. Both the value and the direction of the counter e.m.f are, how-however, modified by the resistance and the reactance voltage drops of the alternating-current motor windings, which variations are proportional to the load.

ϕ_M = The direction of the magnetic flux required to produce OE_M and is 90 degrees in advance.

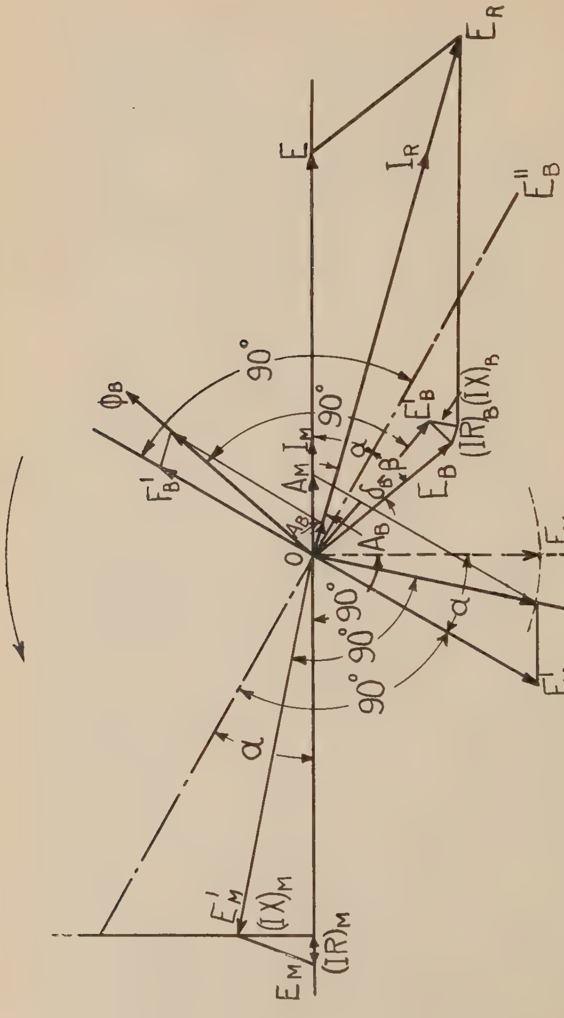


Fig. 289
Vector Diagram of A-C. Motor Generator

F_M = The value of the m.m.f. due to the direct-current ampere-turns required to produce this magnetic flux.

I_M = The load current of the motor. At 100 per cent power-factor, the motor current is in phase with the line voltage OE.

$(IR)_M$ = Resistance voltage drop in the motor armature at full load and in phase with I_M.

$(IX)_M$ = Reactance voltage drop in the motor armature at full load and at right angles to I_M.

OE'_M = Counter e.m.f. of the motor armature as modified in value and direction by the resistance and the reactance voltage drops due to the armature current I_M. As the direction of the flux must always be at right angles to the generated voltage,

ϕ'_M = the direction of the flux required to produce OE'_M. The direction of ϕ'_M with reference to ϕ_M would therefore represent the angular displacement or lag between the two positions of the rotor with no load on the motor and with the motor fully loaded were it not for the demagnetizing action of the alternating current (that is, the armature reaction). The resultant flux as determined by the counter e.m.f. OE'_M must be in the direction of ϕ'_M. This flux is, however, due to the combined magnetomotive forces resulting from the direct-current ampere-turns of the field and the alternating-current ampere-turns of the armature. From the design of the motor—

OA_M = m.m.f. due to the ampere-turns of the armature, its direction being in phase with the alternating current; then

OF'_M = the required m.m.f. due to the ampere-turns of the direct-current field in both value and direction; that is, the resultant flux must be in the direction of ϕ'_M.

The displacement of F'_M from F_M or

Angle α = therefore, the angular displacement of the rotor due to full load from its no-load position or the angle of lag of the rotor under full-load conditions.

The angle is due to the resistance and the reactance voltage drops of the motor armature and to the armature reaction. It increases with the load on the motor, and as may readily be seen, depends on the motor design.

The resistance and reactance of the alternating-current winding and the armature reaction of the booster produce a lag in its terminal voltage, which, with reference to the line voltage, is similar to the mechanical lag of the motor.

Referring again to Fig. 289, if full load on the motor and no load on the booster could be assumed, the booster voltage would be in the direction E''_B for the reason that the rotating direct-current field of both motor and booster occupy the same angular position on a common shaft. It is obvious, however, that both the direction and value of this voltage are modified and vary with the load and the power-factor of the load the voltage of which is regulated.

To simplify the discussion, it will be assumed that full-load current at 100 per cent power-factor is flowing in the line, as, for instance, when the motor-generator is used to regulate the voltage of a synchronous converter. The load current is then in phase with the load voltage regulated by the booster, but as the phase displacement of the booster voltage is as yet unknown, the direction

of the load current with reference to the unregulated voltage is also unknown. It is therefore necessary to approximate the value and the direction of the booster voltage so as to obtain the direction of the line current. This approximation may be obtained from the voltage regulation requirements and the design constants of the booster, although several trials may be required before all of the proper relations are obtained. Assuming for illustration, however, that all of the relations in Fig. 289 are correct, and that

OE_R = the required feeder voltage in value and direction, then as

OE = the unregulated line voltage,

OE_B = the terminal voltage of the booster in value and direction.

OI_R = the direction and value of the current in the booster, and in phase with the regulated voltage. With the direction and the value of the current as now assumed and from the design constants of the booster:

$(IR)_B$ = the resistance voltage drop in the booster at full load, and

$(IX)_B$ = the reactance voltage drop in the booster at full load;

OE'_B = therefore, the voltage generated in the booster under full-load conditions. The m.m.f. producing this voltage is at right angles thereto; that is, in the direction ϕ_B. This m.m.f. is, however, the resultant of the magnetomotive forces produced by the direct-current ampere-turns of the field and the alternating-current ampere-turns of the armature.

OF'_B = the m.m.f. due to the direct-current ampere-turns of the field, this being 90 degrees ahead of the no-load voltage E''_B. This m.m.f. is always in phase with, and opposite to, the m.m.f. OF'_M of the motor, for the reason that, as already stated, both rotors are mounted on and keyed to the same shaft.

OA_B = the m.m.f. due to the alternating-current ampere-turns of the armature, this being in phase with the alternating current. The resultant of these two magnetomotive forces is in the direction ϕ_B as stated. This resultant m.m.f., lagging behind that produced by the direct-current field, causes the generated voltage to lag behind its no-load direction OE''_B. By the impedance of the armature, this lag is further increased to the position and value OE_B. Under full load, therefore,

Angle β = the angle of the voltage lag of the generator, and this lag, as shown, is due to the resistance and reactance of the booster armature winding and the armature reaction. The angle varies with the load and with the power-factor of the load, and depends on the design of the booster.

The motor armature as shown has a mechanical lag behind the line voltage equal to the angle α; whereas, the booster has a voltage lag behind the mechanical lag of the motor equal to angle β. Therefore,

Angle $\alpha+\beta$ = the total angular displacement between the terminal voltage of the booster and the line voltage; that is, the total angle of lag.

It has been assumed that the power-factor of the load is 100 per cent, and as the load voltage is the resultant of the line voltage OE and the booster voltage OE_B (that is, OE_R which is also the direction of the load current), it follows that the power-factor of the booster is the cosine of the angle δ_B.

As the power-factor of the load decreases, the angular displacement of the booster voltage increases; but, with the same load current in the booster, the load on the motor decreases and, hence, the motor lag decreases. A varying power-factor load may or may not, therefore, change the total lag angle of the booster set, depending on the design constants of its two members.

In a like manner it may be shown that a similar phase displacement of the voltage occurs when the voltage is lowered; that is, when the series machine acts as the motor and the shunt machine acts as the generator.

The angle of displacement between the line voltage and the booster voltage obtained with synchronous machines of normal design is approximately 45 degrees. This requires an over-ratio in the booster of about 35 per cent if the load, the voltage of which is to be regulated, has a power-factor of 100 per cent.

It is possible to compensate for the angular displacement of the voltage by having the booster stator adjustable in its angular position to the stator of the motor, or to obtain the voltage range by a sufficient over-ratio in the booster winding. The first arrangement increases the cost, and the second increases the kv-a. capacity of the set with a corresponding increase in the cost and losses.

This design of regulator can be adjusted by hand or can be automatically controlled by a generator voltage regulator. If automatically controlled, it responds to

changes in the voltage requirements in much less time than it is possible to obtain in the induction type; that is, the voltage regulation corresponds to that obtainable with any generator controlled by a generator voltage regulator.

Because of the better ventilation obtainable in the windings of rotating machines, it is customary to operate them at a higher current density than feasible for similar windings in a stationary design, such as in an induction regulator. This increases the copper losses and results in a decrease in the efficiency of the rotating machine which efficiency is further decreased by friction and windage.

Each of the synchronous machines has a kv-a. capacity equal to that of an induction regulator capable of producing the same voltage range. The total efficiency of the set is therefore the product of the efficiencies of the individual machines which combined efficiency is considerably lower than that of an induction regulator of corresponding size. In comparing costs, the difference in the efficiencies should therefore be considered, and the cost of the excess losses in the motor-generator should be capitalized and credited to the cost of the induction regulator.

This design of regulator can be furnished for any voltage or current capacity for which it is practicable to build generators, and it can be furnished for any voltage range.

Synchronous Condensers

The synchronous condenser may be considered as a feeder voltage regulator and it may be operated as such. It is connected across the line, the voltage of which is to be regulated instead of in series with it as is the case in the designs of regulators so far described. The synchronous condenser is installed and connected to the line at the location where the voltage is to be regulated, and the

voltage regulation is obtained by supplying a leading or lagging current (as conditions may require) to the line. The voltage regulation obtainable is governed by the characteristics of the transmission line including the step-up and the step-down transformers. The operation is briefly as follows:

Characteristics of Feeder and Load

As has previously been stated and illustrated, the voltage drop in a feeder is due to both the ohmic and reactive resistances of the line. That due to the former is in phase with, and that due to the latter is at right angles to the line current. The impedance voltage drop for a given line and due to a given current is constant regardless of the power-factor of the load, but the resultant voltage drop in the line, that is, the numerical difference between the bus voltage in the generating station and at the load, is dependent on the power-factor of the load. In Fig. 290,

OI = the line current in value and direction;
OA = the voltage required at the load;
$\cos \alpha$ = the power-factor of the load;
AB = the ohmic line drop due to OI and in phase with it;
BC = reactive line drop due to OI and at right angles to it; then
AC = the impedance voltage drop in the line; and
OC = the voltage required at the station to supply the voltage OA at the load.

The numerical value of AC, the impedance voltage drop in the line, is always directly proportional to the line current, and from the diagram, it is obvious that, with a constant required value of the load voltage OA and for a given line current, the value of OC is dependent on the angle α; that is, on the power-factor of the load.

As shown in the diagram, by rotating I to I' until α is equal to zero (that is, with a 100 per cent power-factor load and for the same current as before), the voltage required at the station, that is, OC' is now less than OC.

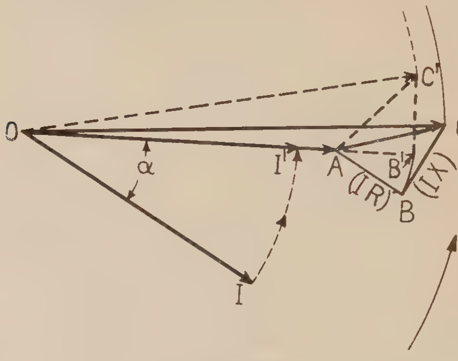


Fig. 290
Vector Analysis Line Characteristics

For a given power requirement, it is however, obvious that the power-factor of the load itself cannot be changed. In other words, an inductive load requires a lagging current and a capacity load requires a leading current, the angular displacement of the current with reference to the voltage (that is, the power-factor) being determined by the load.

Any leading or lagging current may, however, be considered as consisting of two components respectively in phase with and at right angles to the load voltage. The former current is designated as the energy current and the latter as the wattless current. The relative values of these currents are determined by the power-factor of the load, the angular displacement between the total current and the energy current being the displacement between the total current and the load voltage.

The current OI assumed in Fig. 290 may therefore be resolved into the two components as shown in Fig. 291.

OA = the load voltage as in Fig. 290,

OI = the load current,

OI' = the energy current,

II' = the wattless current.

The impedance voltage drop AC in Fig. 290 is due to the current OI in Fig. 291, and, as previously stated, is directly

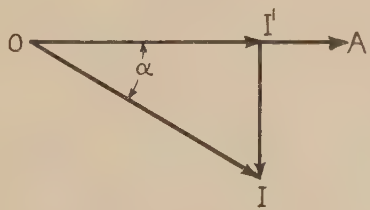


Fig. 291
Vector Analysis of Energy and Wattless Currents

proportional to this current and is also modified by the angular relation of this current to the line voltage.

If, therefore, the energy required by the load could be transmitted over the line at 100 per cent power-factor and the wattless current component required by the load could be supplied at the load, then the line drop would be reduced in proportion to the reduction in the current transmitted and further modified by the change in the angular displacement between the line current and the voltage. This may be illustrated as in Fig. 292, using the same designations as in Figs. 290 and 291.

If a leading wattless current, $I'I''$ and equal to the lagging wattless current $I'I$ required by the load is supplied at the load, the resultant line current becomes OI'. The

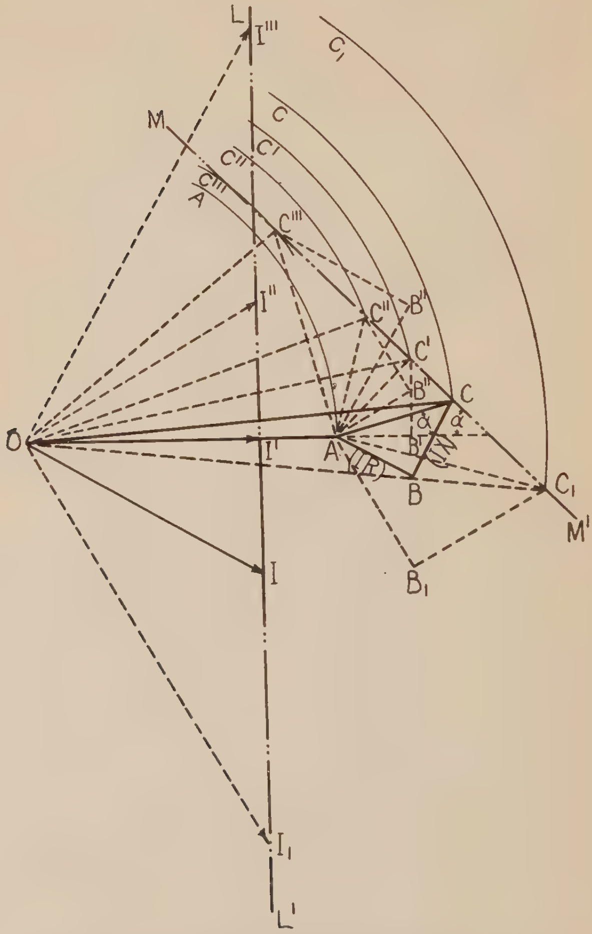


Fig. 292
Voltage Regulation Obtainable by the Supplying Wattless Current at the Load

impedance voltage drop AC is then reduced in proportion to the reduction in the line current as AC', and its angular position with respect to the line voltage OA is changed so as to reduce the voltage required at the generating station from OC to OC'.

Increasing the leading current still further (as, for instance, so that the line current becomes OI'' and leading) again increases the actual impedance drop from AC' to AC''. However, due to the further change in the angular position of this voltage drop with respect to the line voltage, the voltage required at the generating station as OC'' is again decreased.

Increasing the leading current so that it greatly exceeds the energy component, as for instance, to the value of $I'I'''$, still reduces the voltage required of the generating station as OC''' but the line losses are now rapidly increasing.

The change in the voltage required from the generating station may be illustrated further by assuming an increase in the lagging current, as, for instance, from I to I_1. The diagram shows that the addition of a lagging current II_1 to the lagging current II' required by the load increases the voltage required of the generating station to OC_1.

This diagram also shows that, if the load current be leading as I'', the addition of a lagging current as $I'I$ increases the generating station voltage required, as from OC'' to OC', but decreases the resultant line current and hence decreases the line losses.

The minimum line loss is obtained with a 100 per cent power-factor load on the line (that is, with the current in the direction of and having the value OI'), and any increase in the line current increases the loss in the ratio of the square of the current flowing.

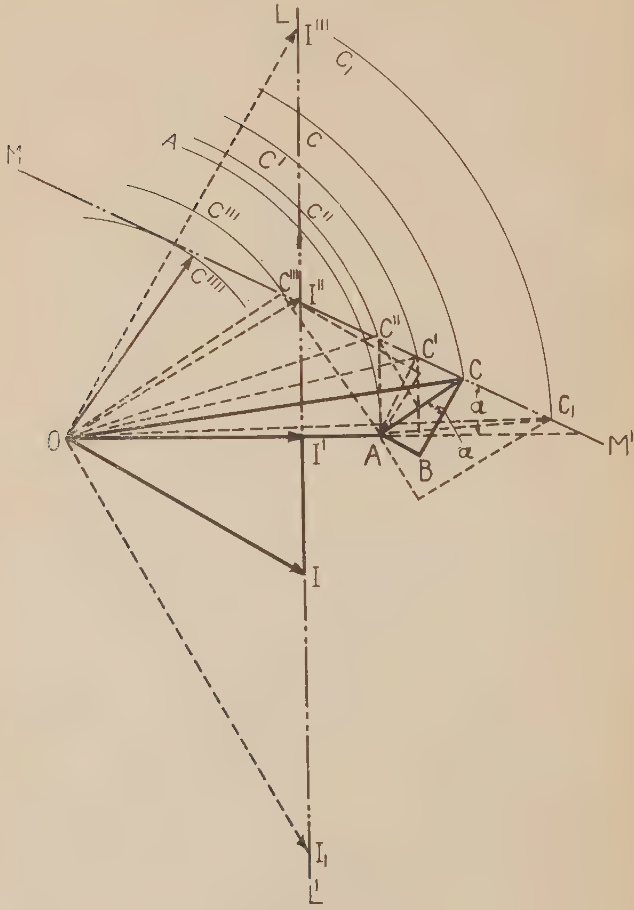


Fig. 293
Voltage Regulation Obtainable by the Supplying Wattless Current at the Load

With the line conditions assumed, that is, with the resistance equal to the reactance, the voltage required at the generating station can never be reduced to the required load voltage by the addition of wattless current.

With the energy component of the current equal to OI', the line LL' is the locus of all line currents regardless of the value of the leading or lagging currents introduced. The impedance drop AC has a definite angular position with reference to the current and varies in value directly with the current. The line MM' is therefore the locus of the impedance voltage drops and, hence, of the generating station voltages required for the various conditions assumed. In the case considered and as shown in the diagram, the line MM' can never become tangent to or cut the arc of the circle drawn with the load voltage OA as a radius, regardless of the amount of leading current supplied to the line.

As stated, however, the generating station voltage required depends on the characteristics of the line; viz, the relative values of its resistance and its reactance. The greater the line reactance with reference to its resistance, the greater is the voltage variation obtainable. This may be illustrated by Fig. 293 which is identical to Fig. 292 except that the line resistance is one-half of the value assumed in Fig. 292. Increasing the reactance or decreasing the resistance of the line changes the angle of the locus of the impedance voltage, that is, of the line drop MM' and, hence, changes the distance of this line from the point O. In the last case assumed, it will be noted that, by adding a sufficiently large leading current to the line, the voltage at the load may be greater than the voltage in the generating station in spite of the fact that the impedance drop and the line loss are thereby increased.

With the line constants assumed in Fig. 293, OC'''' is the minimum voltage in the generating station which will give the required voltage of OA at the load. OC'''' is the radius of the circle to which MM' is tangent, and it will be noted in the diagram that the voltage required at the load, that is OA, greatly exceeds the voltage required at the generating station.

With a given station bus voltage, it is therefore obvious that a voltage regulation may be obtained at the load by supplying the line, at the point where the load is connected, with a wattless leading or lagging current and that the voltage regulation obtainable depends on the resistance and reactance of the line.

Characteristics of Synchronous Condensers

If a synchronous motor is connected to a line and is not connected to a load, the power required by the motor is just sufficient to supply the motor losses. The alternating current in the motor may, however, be varied by changing the direct-current field excitation. With 100 per cent field excitation, the counter e.m.f. of the motor due to the direct-current field is practically equal to the line voltage, and the alternating current has a minimum value. Under this condition, the power-factor of the motor is practically 100 per cent. With less than normal excitation, the counter e.m.f. due to the direct-current field is less than the line voltage, and a greater current will flow from the line into the motor. For the same reason, if the motor excitation is greater than 100 per cent, its counter e.m.f. is greater than the line voltage, and a current must flow from the motor into the line.

This condition may be illustrated by Fig. 294. The e.m.f. curve of the motor represents the open-circuit voltage across the motor terminals for a varying direct-current

excitation with the motor driven as a generator. As the motor terminals are, however, connected across the line, it is obvious that the motor terminal voltage must always

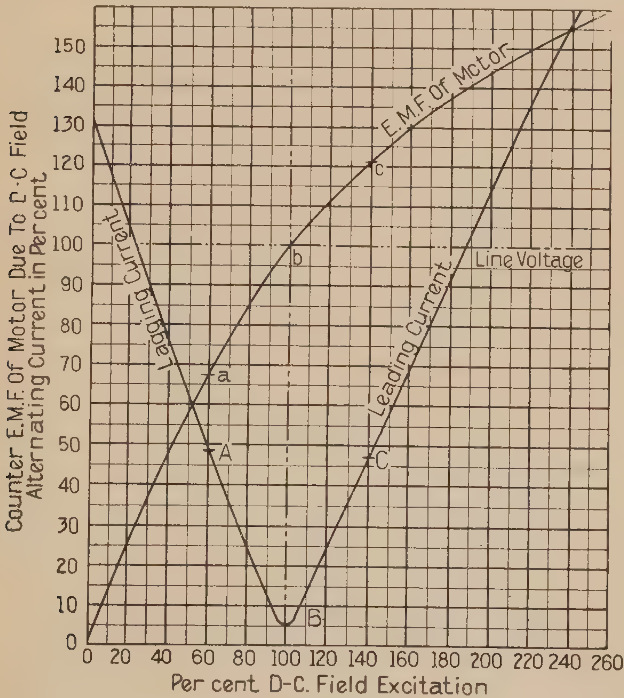


Fig. 294
Characteristics of Synchronous Condenser

be equal to the line voltage. Disregarding, for the sake of simplicity, the varying voltage drop in the armature due to different values of the current, the difference between the motor voltage due to the direct-current field and the line voltage must therefore be obtained by means of the mag-

netization of the field by the current in the armature itself. A lagging current in the armature augments the magnetic field due to the direct-current field excitation and a leading current deducts therefrom, and, as the total counter e.m.f. of the motor must equal the line voltage, the armature current (leading or lagging) is therefore definitely controlled by the direct-current field adjustment.

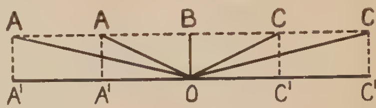


Fig. 295
Vector Analysis of Energy and Wattless Current

In Fig. 294, the variation of the alternating current in the motor is indicated by the curve *ABC*. The current at *B* is the energy current at 100 per cent excitation required to supply the losses in the motor itself, that is, with this direct-current field excitation, the counter e.m.f. of the motor is practically equal to the line voltage as at *b*. The currents *A* and *C* are the resultant of the energy current and the lagging and leading currents respectively flowing in the armature at less than and greater than 100 per cent field excitation. These currents may be resolved into their energy and wattless components as in Fig. 295. Whatever the total current and regardless of whether it is leading or lagging, the energy component is always *BO*. The total current is represented by *AO* and *CO*, and the wattless component is represented by *A'O* and *C'O*, respectively. The wattless component of the current *AO* in Fig. 295 is always, just sufficient to increase the direct-current field excitation so that the motor terminal voltage will be normal instead of as at *a* in Fig. 294. The wattless component of the current *CO* is likewise always just sufficient to decrease the field excitation to normal instead of having a value such as shown at *c*.

The current curves shown in Fig. 294 are not symmetrical because of the voltage drop in the armature due to the varying current flowing and also because the direct-current magnetization curve (designated as the motor e.m.f.) is not symmetrical. The curve given is, however, characteristic of all synchronous condensers, although its detailed construction depends on the design constants of the condenser.

A consideration of this general characteristic curve in conjunction with the discussion of the "Characteristics of Feeder and Load" and the diagrams Figs. 292 and 293 given with this discussion will serve to illustrate the manner in which a leading or lagging current may be supplied at the load and a voltage regulation obtained at the load for different conditions of load and with a constant voltage supplied by the generator.

Kv-a. Capacity of Synchronous Condenser

For any given power transmitted over a given line, the required kv-a. capacity of the synchronous condenser is governed by the power-factor of the load. On the assumption that it is desired to transmit energy at 100 per cent power-factor, the kv-a. capacity of the condenser has the same ratio to the actual kw. transmitted as the wattless component of the load current has to the energy component; that is, the wattless component is the tangent of the angle the cosine of which represents the power-factor. This may be illustrated by Fig. 296. It will be noted that the kv-a. capacity of the synchronous condenser, expressed in percentage of the wattless component to the actual power transmitted, increases very rapidly with a decrease in the power-factor of the load, being equal to the kw. capacity of the load at a power-factor of about 70 per cent. It also

will be noted that the line kv-a., and hence, the line current, also increases rapidly and at an increasing rate. As the line drop is due to the line current and to the phase dis-

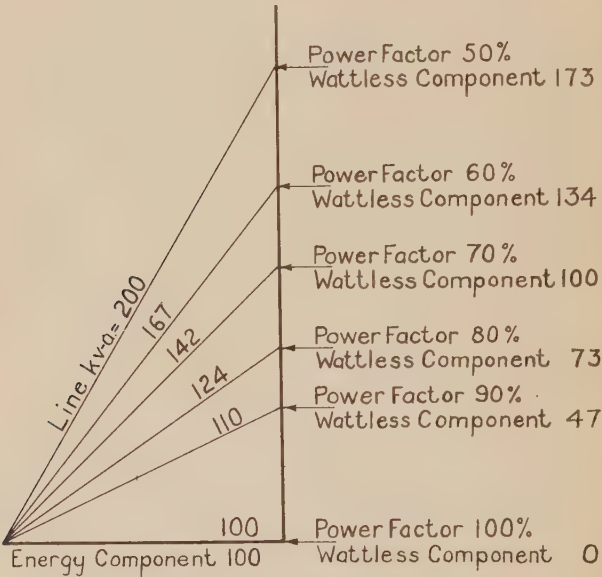


Fig. 296
Relation Between the Energy Component, the Wattless Component and the Kv-a. for Various Power-Factors

placement of this current with respect to the line voltage, it is of much greater advantage to increase the power-factor from 50 to 60 per cent, for instance, than to increase it from 90 to 100 per cent. Because of the relatively small advantage gained, and because of the comparatively large kv-a. capacity of the synchronous condenser required, to increase the power-factor of the load carried by the line to some reasonable and economical value is preferable and

more economical than to increase the power-factor to 100 per cent by this means.

The kv-a. capacity of the condenser for such cases will be equal to the difference between the kv-a. required to increase the power-factor to 100 per cent and the kv-a. required to increase it from the power-factor at which the energy is to be transmitted to 100 per cent.

For instance, if the power-factor of the load is 50 per cent, requiring a 173 per cent condenser to increase the power-factor of the load on the line to 100 per cent power-factor and it is decided to operate the line at 90 per cent power-factor, requiring a 47 per cent condenser, the condenser required for the conditions given will have a capacity of 173 − 47 or 126 per cent of the actual kw. to be transmitted.

By means of a generator voltage regulator the synchronous condenser when used as a regulator has the advantage, in common with the series booster, of correcting voltage variations practically as soon as the voltage variations occur. As the voltage increase may be produced partly by a reduction in the line current, the current in the generator being reduced by a corresponding amount, the use of a synchronous condenser has the further advantage of thereby increasing the load capable of being carried by the generator, transformers, and line, provided the prime mover is large enough to carry the maximum output of the generator at 100 per cent power-factor.

By referring to Figs. 292 and 293, however, it will be observed that the value of the synchronous condenser as a regulator is dependent on the line constants. For a given line drop, it is more effective if the reactance component predominates and less effective if the resistance component

predominates. If synchronous condensers are installed to supply the lagging current required by the load (thereby to increase the line and generator capacity), it may therefore be found advisable and economical also to install an induction regulator for voltage regulation if the line has a high resistance and low reactance voltage drop, or to increase the line reactance by the use of a series reactance. The latter is also advantageous in limiting the short-circuit current. This use of a current-limiting reactance is in no way detrimental, but, rather, is advantageous, wherever synchronous condensers or synchronous motors are used for power-factor correction.

The disadvantage of this method of voltage regulation is its low operating efficiency compared with that of an induction regulator. The efficiencies of the condenser and the induction regulator may be identical; but because of the larger kv-a. condenser capacity required, the total loss due to the former is larger than that due to the latter. Under some conditions, this increase in the losses may be offset by a reduction in the transmission losses, but, as may be observed in Figs. 292 and 293, it may be offset only in case the power-factor of the line is increased above its normal value.

It also will be observed from Fig. 293, that while the line loss may be decreased by boosting the voltage by means of a condenser, it is increased when lowering the voltage; that is, the lowering of the voltage at the load is obtained primarily by loading the line with a lagging current, thereby increasing the line drop and, hence, the line losses.

The synchronous condenser is of unquestionable value for the voltage control of long high-voltage lines carrying either leading or lagging current; but, obviously, it is not

economical for the voltage control of low-potential distributing feeders. Such feeders are usually of limited capacity and supply both power and lighting loads, and in an increasing number of installations, require individual phase regulation of the voltage.

For low-voltage distributing systems carrying power or mixed power and lighting loads, the synchronous condenser will, however, in many cases be found advantageous if used as a power motor and only partly loaded. A 70 per cent power current load and a 70 per cent wattless current load have been found to be an advantageous arrangement. With regard to the heating of the windings, a 70 per cent power load and a 70 per cent wattless load at right angles to it is equal to a normal 100 per cent load. When so used, it may, however, be necessary to make some special arrangement with the purchaser of the power because a synchronous motor is more expensive than an induction motor capable of doing the same mechanical work, and to be effective, the synchronous machine should be equipped with an automatic generator voltage regulator. As the power company is the beneficiary and as no advantage is gained by the purchaser of the power, the extra cost may therefore justly be borne by the operating company.

The synchronous condenser can be built for any voltage or current for which it is practicable to build generators, and for high-potential systems, may be used with step-up transformers.

Static Condensers

The static condenser performs the same function as the synchronous condenser in supplying a leading current to the line; but it cannot supply a lagging current. It consists of built-up condenser sections connected in

multiple, and the combination is connected across the line or feeder through a suitable switch and series reactance. Voltage control may be obtained by varying the leading

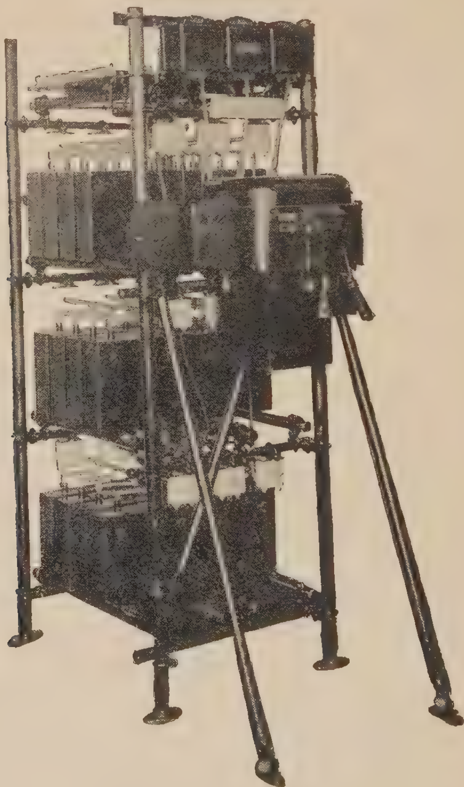


Fig. 297
Indoor Static Condenser

current supplied to the line by cutting in or out condenser sections. The obtainable voltage control, reduction in generating and transmission losses, and increased power-

carrying capacity of the generating and transmission system are similar to those obtainable with a synchronous condenser supplying a leading current, and the kv-a. capacity required is similarly determined.

The general design of the static condenser developed for this purpose by the General Electric Company is shown in Fig. 297. As designed, it is not adjustable and is intended primarily for power-factor correction rather than for voltage regulation; that is, the condenser is intended only as a means for increasing the actual power capacity of the generator, transformer, and feeder. The improvement of the power-factor of a system, however, also decreases the voltage drop, for the two functions are interrelated.

The static condenser is exceedingly simple in construction and requires no attention. It has an exceedingly high efficiency and can be used economically in much smaller sizes than the synchronous condenser. Sizes from 50 to 400 kv-a. and for voltages of from 400 to 2300 have been standardized.

General Conclusions

As will be noted from the preceding discussion, the cost of voltage regulation increases with the quality of the service. The regulator having the lowest cost is also the most efficient, but with such a regulator the regulation is in steps. The voltage changes are made by hand, and they are therefore necessarily intermittent. The regulator having the highest cost has a low efficiency, but it automatically maintains a practically constant voltage, and by changing the power-factor of the load on the line may reduce the generating and transmission losses.

There are, however, applications for all of the methods of voltage control, and the selection depends on the requirements

of the service, on the adaptability of the apparatus used for voltage control to the requirements, and—if there is a choice in design—on the cost. The cost, as already indicated, consists of the initial cost of the regulating apparatus, or rather the interest and depreciation thereon, plus the cost of the net losses due to the use of the apparatus as a regulator. Each requirement must therefore be analyzed to insure that the apparatus selected will be the most satisfactory and economical. However, as has been previously stated, practically all feeder voltage regulation is obtained by means of the induction regulator, the chief reasons being as follows:

The induction regulator can be built economically in any size from 100 watts up to maximum requirements and for any voltage for which it is practicable to build generators or motors. The voltage regulation obtained is gradual and not in steps. The induction regulator may be operated by hand or automatically without a material change in design. The efficiency of this design of regulator is high, and the initial and operating costs are not excessive.

The step-by-step method of regulation is, in general, unsatisfactory because close adjustments of voltage cannot be obtained and because of the necessity of switching the current to the feeder to be controlled. The series synchronous booster and the synchronous condenser are expensive and uneconomical in the kv-a. capacities for which the majority of regulators are required. The static condenser is not adjustable and it cannot economically be made so.

The induction regulator being, however, applicable to practically all requirements, and having been found exceedingly satisfactory and economical, has therefore been developed to its fullest extent as indicated in the preceding pages, and as summarized and further illustrated in Figs. 298 to 301 inclusive.

THE REGULATION OF LIGHTING FEEDERS

Built in Sizes to Control Single-Phase, 2300-Volt, 60-Cycle Circuits of from 25 to 300 Amperes and to Produce a Voltage Range of 20 Per Cent, and for Three-Phase Circuits of from 25 to 200 Amperes. Oil-Immersed, Self-Cooled. Occupies a Minimum Floor Space and is Furnished with or without Panel for the Auxiliaries as may be Desired

Outdoor Type. Built in the Same Sizes as Above. The Casings are of Heavy Sheet Iron Construction and are Weatherproof. All Parts Requiring Inspection are Readily Accessible

Pole Type. For Single-Phase, 2300-Volt, 60-Cycle Circuits up to 25 Kw., Producing a Voltage Range of 20 Per Cent, Designed for Mounting on a Pole at the Junction of a Lighting Feeder Tapped from a Power Circuit. Absolutely Reliable and Requires Little Attention

Fig. 298
Regulators for Lighting Feeders

THE REGULATION OF POWER FEEDERS

Oil-Immersed, Self-Cooled Design Built in Sizes from 70 to about 300 Kv-a., for 60-Cycle, 2300-Volt Circuits, and in Corresponding Sizes for Other Frequencies and Voltages. Can be Arranged for Outdoor Substations if Desired

Oil-Immersed, Water-Cooled Design Built in Sizes from 100 to 1000 Kv-a., 60 Cycles, 14,000 Volts
Corresponding Kv-a. Capacities for Other Frequencies

Air-Blast Design Built in Sizes from 100 to 60 Kv-a., 60-Cycle, 6600-volt Circuits. Can b Arranged for either Bottom-Connected Lead as shown, or for Top-Connected Leads as in th Oil-Immersed Type

Fig. 299
Regulators for Power Feeders

SPECIAL APPLICATIONS

Miniature Regulators in Capacities from 100 Watts to 1 Kv-a., 60 Cycles, 110 Volts, either Single-Phase or Polyphase, and for Any Range in Voltage. Used for Small Furnaces, High-Voltage Testing Sets, Calibration Sets and Laboratory Work

Small Hand-Operated Self-Cooled Regulators Wound for 2300-Volt, Single-Phase Circuits, and for Capacities up to 4 Kv-a., 60 Cycles. Used to Control the Primary Voltage of Special Transformers Having High Secondary Current Capacities

Large High-Current Regulator. Capacity 770 Kv-a., Single-Phase, 25 Cycles, 10,000 Amperes. Can be Furnished in Any Standard Design, Single-Phase or Polyphase, and for Any Reasonable Requirement and for Any Range in Voltage

Fig. 300
Regulators for Special Applications

A G-E INDUCTION REGULATOR FOR EVERY VOLTAGE REGULATION REQUIREMENT

100 to 1000 Watt, 60-Cycle, 110-Volt, Single-Phase or Polyphase

1 to 4 Kv-a., 60-Cycle, 2300-Volt, Single-Phase

2.5 Kv-a., 60-Cycle, 2300-Volt, Single-Phase Automatic

5 to 70 Kv-a., 60-Cycle, 2300-Volt, Single-Phase or Polyphase, Self-Cooled

70 to 300 Kv-a., 60-Cycle, 2300-Volt, Single-Phase or Polyphase, Self-Cooled

100 to 1000 Kv-a., 60-Cycle, 14,000-Volt, Single-Phase or Polyphase, Oil- and Water-Cooled

100 to 600 Kv-a., 60-Cycle, 14,000-Volt, Self-Cooled

100 to 600 Kv-a., 60-Cycle, 6600-Volt, Air-Blast

770 Kv-a., 25-Cycle, 10,000-Amp., Single-Phase, Oil- and Water-Cooled

5 to 70 Kv-a., 60-Cycle, 2300-Volt, Single-Phase or Polyphase, Outdoor Type

200 to 600 Kv-a., 60-Cycle, 2300-Volt, Single-Phase or Polyphase, Outdoor Type

The Regulator Department, at Pittsfield, Mass.

Fig. 301

Typical Regulators Showing the Variety Available

SECTION XXVIII

THE INCREASING USE OF THE INDUCTION VOLTAGE REGULATOR

The number of induction regulators used for various purposes is increasing from year to year as indicated in Fig. 302. The average size of the unit is also increasing both for industrial and illuminating requirements. During the first few years after the induction regulator was introduced by the General Electric Company, the average size used for lighting feeders was approximately 10 kv-a.; whereas, at present, the average size is approximately 40 kv-a. Regulators for power circuits are also being used much more extensively and for higher voltages than heretofore. Regulators of 600 kv-a. capacity and others wound for 14,000-volt circuits are used on a number of generating and distributing systems.

The use of regulators for outdoor installations is also increasing, and as indicated in Section XXII, any size of regulator either for single-phase or polyphase requirements, and wound for any voltage for which the station type can be designed, can be so furnished.

In anticipation of the increasing demand for this class of apparatus, the General Electric Company has equipped a large factory building with the most modern, standard and specially designed machine tools for the exclusive manufacture of the induction voltage regulator. The entire time of a large engineering staff of specialists is also devoted to the study of feeder voltage regulation, and to the design, construction and manufacture of induction voltage regulators and their auxiliaries.

As indicated in the preceding sections, every problem pertaining to the design, manufacture, operation or requirements of the induction voltage regulator has been

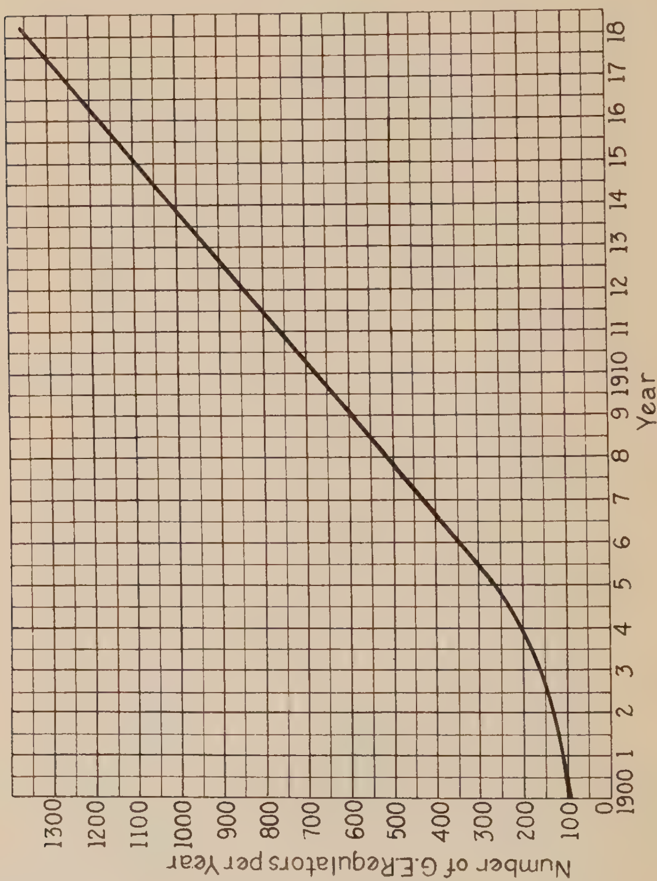


Fig. 302
Curve Showing the Increasing Use of the Induction Regulator

studied in detail and the results have been incorporated in the finished product.

The following tabulations indicate the extensive use of the induction regulator. Table I indicates the voltages for which regulators have been wound; Table II lists the larger sizes of regulators built; and Table III, gives a list of operating companies which use General Electric Company regulators more or less extensively. Table III is necessarily incomplete because of the purchase of regulators by agencies, holding companies, and contracting engineers. It, however, serves to indicate the extensive use and general appreciation of this class of apparatus.

TABLE I

REGULATORS WOUND FOR 10,000 VOLTS AND ABOVE

NUMBER SOLD	TYPE	KV-A.	FRE-QUENCY	PRIMARY VOLTS	CUSTOMER
1	IRT	100	25	11000	Syracuse Lighting Co., Syracuse, N. Y.
1	IRT	130	25	11000	Rochester Rwy. & Lt. Co., Rochester, N. Y.
1	IRT	150	60	11000	Hartford Elec. Lt. Co., Hartford, Conn.
1	IRT	150	60	11000	Pacific Gas & Elec. Co., San Francisco, Calif.
11	IRT	160	50	11000	Southern California Edison Co., Los Angeles, Calif.
1	IRT	173	60	10500	Central Colorado Pwr. Co., Denver, Colo.
2	IRS	175	60	12000	Great Western Pwr. Co., San Francisco, Calif.
3	IRT	300	40	10800	Hudson River Elec. Co., Glens Falls, N. Y.
2	IRT	300	25	11000	Mississippi River Pwr. Co., Keokuk, Iowa
3	IRT	300	60	12000	Great Western Pwr. Co., San Francisco, Calif.
3	IRT	300	60	13800	Blackstone Valley Gas & Elec. Co., Pawtucket, R. I.
2	IRT	335	40	12000	Adirondack Elec. Pwr. Co., Watervliet, N. Y.
1	IRT	500	60	11000	Hartford Electric Lt. Co., Hartford, Conn.
1	IRT	690	60	10750	Great Western Pwr. Co., San Francisco, Calif.
1	IRT	1000	60	11000	Hartford Elec. Lt. Co., Hartford, Conn.

TABLE II
REGULATORS OF 500 KV-A. CAPACITY AND ABOVE

NUMBER SOLD	TYPE	KV-A.	FRE-QUENCY	PRIMARY VOLTS	SECOND-ARY AMPERES	CUSTOMER
1	IRQ	500	60	2300	1100	Newburg Lt., Ht. & Pwr. Co., Newburg, N. Y.
1	IRQ	500	60	2300	1100	Seattle Tacoma Pwr. Co., Seattle, Wash.
1	IRT	500	60	11000	263	Hartford Elec. Lt. Co., Hartford, Conn.
2	IRT	530	25	9000	245	Commonwealth Edison Co., Chicago, Ill.
1	IRS	535	25	185	7500	Cataract Const. Co., Niagara Falls, N. Y.
1	IRS	560	25	140	9350	Acheson Graphite Co., Niagara Falls, N. Y.
1	IRS	560	25	140	9350	Carborundum Works, Niagara Falls, N. Y.
1	IRS	600	25	185	8450	Cataract Const. Co., Niagara Falls, N. Y.
1	IRT	600	60	2300	1500	Palmetto Pwr. Co., Hartsville, S. C.
12	IRT	600	60	2300/4600	1500/750	Detroit Edison Co., Detroit, Mich.
1	IRT	625	60	2300	1570	Hartford Elec. Lt. Co., Hartford, Conn.
2	IRT	690	60	5000	800	Eastern Michigan Pwr. Co., Jackson, Mich.
1	IRT	690	60	10750	265	Great Western Pwr. Co., San Francisco, Calif.
1	IRS	700	25	145	10000	Canadian Gen. Elec. Co., Niagara Falls, N. Y.
1	IRS	700	25	145	10000	Norton Co., Niagara Falls, N. Y.
1	IRS	750	25	2200	800	Pittsburg Reduction Co., Niagara Falls, N. Y.
1	IRQ	750	60	5500	684	United Elec. Lt. Co., Springfield, Mass.
1	IRQ	750	60	5500	684	Turners Falls Pwr. Co., Springfield, Mass.
1	IRS	770	25	160	10000	Electrometallurgical Co., Niagara Falls, N. Y.
1	IRT	800	60	2400	2320	Montreal Lt., Ht. & Pwr. Co., Montreal, Canada
1	IRT	800	60	6600	466	Great Falls Pwr. Co., Great Falls, Mont.
1	IRT	1000	60	11000	526	Hartford Elec. Lt. Co., Hartford, Conn.

TABLE III

CUSTOMERS USING TEN OR MORE G-E CO. REGULATORS AND THE NUMBER AND CAPACITY OF THE REGULATORS PURCHASED TO JAN. 1, 1920

CUSTOMER	NUMBER OF UNITS	KV-A. OF UNITS	TOTAL KV-A.
Adirondack Lt. and Pwr. Co., Schenectady, N. Y.	13	2.3 to 34	350
Allegheny County Light Co., East Liberty, Pa.	13	11 to 46	455
Atlanta Gas & Elec. Co., Easton, Pa.	16	11.5 to 57.5	368
Australian Gen. Elec. Co., Sydney, Australia	36	4 to 175	1622
Bagnall & Hilles, Yokohama, Japan	22	10 to 75	506
Bangalore, India	10	11	110
Birmingham Rwy., Lt. & Pwr. Co., Birmingham, Ala.	27	11 to 50	643
B.T.H. Co., Rugby, England	48	1 to 234	913
Brooklyn Edison Co., Brooklyn, N. Y.	184	1 to 150	4744
Buffalo Gen. Elec. Co., Buffalo, N. Y.	53	34.5 to 87	2315
California Gas & Elec. Co.	28	15 to 200	1288
Canadian Gen. Elec. Co., Canada	157	1 to 156	8415
Central Hudson Gas & Elec. Co., Newburg, N. Y.	14	2.3 to 100	415
Central Maine Pwr. Co., Augusta, Me.	18	2.3 to 100	824
Central Mexico Lt. & Pwr. Co., Colorado Springs, Colo.	37	9.5 to 345	3341
C. F. T. H., France	11	5 to 225	344
Cleveland Elec. Ill. Co., Cleveland, Ohio	394	7.5 to 22	3932
Coast Counties Gas & Elec. Co., Santa Cruz, Calif.	11	9.5 to 46	290
Commonwealth Edison Co., Chicago, Ill.	656	2.3 to 530	24660
Commonwealth Pwr. Co., Jackson, Mich.	44	10 to 390	1428
Consolidated Gas, Elec. Lt. & Pwr. Co., Baltimore, Md.	69	2.3 to 24	1273
Consolidated Lt. & Pwr. Co., Kansas City, Mo.	12	22 to 216	759
Connecticut Lt. & Pwr. Co.	21	5 to 300	760
Cumberland County Pwr. & Lt. Co., Portland, Me.	21	23	483
Dallas Elec. Lt. & Pwr. Co., Dallas, Texas	25	2.5 to 48	1020
Dayton Pwr. & Lt. Co., Dayton, Ohio	14	1 to 60	520
Decatur Rwy. & Lt. Co., Decatur, Ill.	12	23 to 36	312
Des Moines Elec. Co., Des Moines, Iowa	18	2.3 to 46	484
Eastern Michigan Pwr. Co.	50	21.6 to 690	8080
Ebro Irrigation & Pwr. Co., Spain	12	30 to 150	1560
Chicago Edison Co., Chicago, Ill.	134	8 to 280	7042
Edison Elec. Ill. Co., Boston, Mass.	273	1 to 76	6120
Detroit Edison Co., Detroit, Mich.	128	2.3 to 600	10172
Edison Elec. Ill. Co., New York City	17	10 to 33	311
Edison Elec. Co., Williamsport, Pa.	16	12 to 200	430
Electric Co. of Missouri, St. Louis, Mo.	16	2.3 to 48	465
Fall River Elec. Lt. Co., Fall River, Mass.	25	22 to 34	605

CUSTOMER	NUMBER OF UNITS	KV-A. OF UNITS	TOTAL KV-A.
General Electric Co., Harrison, N. J.	122	0.5 to 66	493
General Electric Co., Pittsfield, Mass.	77	0.52 to 40	450
General Electric Co., Schenectady, N. Y.	59	1 to 90	1160
General Electric Co., West Lynn, Mass.	10	0.25 to 77	314
General Electric Co., Fort Wayne, Ind.	55	1 to 44	300
Georgia Rwy. & Pwr. Co., Atlanta, Ga.	22	31 to 120	1573
Gillette Safety Razor Co., Boston, Mass.	22	25	550
Great Western Pwr. Co., San Francisco, Calif.	29	15 to 690	4254
Greenfield Elec. Lt. & Pwr. Co., Shelbourne Falls, Mass.	12	11 to 76	242
Guinle & Co., New York City	18	5 to 100	349
Harrisburg Lt. & Pwr. Co., Harrisburg, Pa.	10	17.25 to 60	301
Hartford Elec. Co., Hartford, Conn.	28	2.3 to 1000	3780
City of Holyoke, Holyoke, Mass.	29	11 to 23	332
Houston Lt. & Pwr. Co., Houston, Texas	62	20 to 80	3030
Illinois Northern Utilities Co., Compton, Ill.	27	2.3 to 34	363
Indiana Pwr. & Water Co., Edwardsport, Ind.	16	2.3 to 11.5	92
Indiana & Michigan Elec. Co., So. Bend, Ind.	15	22 to 46	572
Indianapolis Lt. & Ht. Co., Indianapolis, Ind.	31	11 to 23	641
Iowa Elec. Co., Maquoketa, Iowa	16	2.3 to 23	143
Kansas City Elec. Lt. Co., Kansas City, Mo.	54	17.25 to 60	1688
La Clede Gas Lt. Co., St. Louis, Mo.	34	2.3 to 62	1496
Lawrence Gas Co., Lawrence, Mass.	21	15 to 53	540
Lehigh Valley Transit Co., Allentown, Pa.	11	22 to 80	464
Los Angeles Gas & Elec. Co., Los Angeles, Calif.	18	1 to 80	1221
City of Los Angeles, Los Angeles, Calif.	30	38 to 95	1674
Los Angeles Edison Co., Los Angeles, Calif.	42	9.5 to 83	2062
Louisville Gas & Elec. Co., Louisville, Ky.	29	34 to 46	1320
Luzerne Gas & Elec. Co., Nanticoke, Pa.	12	11.5 to 23	230
Lynn Gas & Elec. Co., Lynn, Mass.	32	15 to 60	840
Mahoning & Shenango Rwy. & Lt. Co., Newcastle, Pa.	22	12.5 to 33	440
Manchester Trac., Lt. & Pwr. Co., Manchester, N. H.	35	33 to 380	1867
Manila Elec. R.R. & Lt. Co., Manila, Pa.	24	25.5 to 86	720
Mitsui & Co., Japan	19	23 to 57	608
Milwaukee Elec. Rwy. & Lt. Co.	276	1 to 208	8075
Minneapolis Gen. Elec. Co., Minneapolis, Minn.	76	2.3 to 80	2185
Montreal Lt., Ht. & Pwr. Co., Montreal, Canada	13	40 to 800	1637
Narragansett Elec. Lt. Co., Providence, R. I.	32	2.3 to 150	1460
Nashville Rwy. & Lt. Co., Nashville, Tenn.	21	11.5 to 125	1055
National Quality Lamp Division, Cleveland, Ohio	36	10 to 50	740
New Bedford Gas & Edison Lt. Co., New Bedford, Mass.	15	1 to 40	395
New York Edison Co., New York City	155	2.5 to 375	11972

TABLE III (Cont'd)

CUSTOMER	NUMBER OF UNITS	KV-A. OF UNITS	TOTAL KV-A.
New York & Queens Elec. Lt. & Pwr. Co., Long Island City, N. Y.	20	1 to 46	1121
Norfolk & Portsmouth Traction Co.	11	28.5 to 76	481
Northern Indiana Gas & Elec. Co., Hammond, Ind.	13	11 to 46	413
Northern States Pwr. Co.	36	5.75 to 80	1137
Northwestern Elec. Co., Portland, Ore.	20	5.75 to 60	756
North Shore Elec. Co., Chicago, Ill.	39	11 to 22	606
Oakland Lt. & Ht. Co., Oakland, Calif.	15	30 to 150	1080
Omaha Elec. Lt. & Pwr. Co., Omaha, Neb.	38	11.5 to 138	1322
Orange & Rockland Elec. Co., Monroe, N. Y.	11	5.75 to 11.5	103
Osaka Elec. Lt. Co., Osaka, Japan	15	25	375
Pacific Gas & Elec. Co., San Francisco, Calif.	51	17.5 to 300	2990
Pacific Pwr. & Lt. Co., Portland, Ore.	10	28.5 to 150	752
Penn. Central Lt. & Pwr. Co., Altoona, Pa.	20	2.3 to 34	304
Peoria Gas & Elec. Co., Peoria, Ill.	10	11.5	115
Philadelphia Elec. Co., Philadelphia, Pa.	339	10 to 400	9982
Phoenix Construction Co.	56	10 to 40	1460
Portland Rwy., Lt. & Pwr. Co., Portland, Ore.	31	5 to 46	907
Potomac Elec. Pwr. Co., Washington, D. C.	48	2.3 to 37.5	674
Public Service Co. of Northern Illinois, Chicago, Ill.	88	2.3 to 69	2262
Public Service Elec. Co., New Jersey	306	2.3 to 175	10880
Puget Sound Trac., Lt., Ht. & Pwr. Co., Seattle, Wash.	12	11.5 to 46	283
Rio de Janeiro Trac., Lt. & Pwr. Co., Rio Janeiro, Brazil	25	1 to 302	3114
Rochester Rwy. & Lt. Co., Rochester, N. Y.	52	15 to 195	1500
Sanitary District of Chicago, Chicago, Ill.	19	2 to 20	353
San Antonio Gas & Elec. Co., San Antonio, Texas	30	22 to 34	708
San Diego Consolidated Gas & Elec. Co., San Diego, Calif.	14	34.5	506
San Francisco Gas & Elec. Co., San Francisco, Calif.	30	44	1320
Seattle Electric Co., Seattle, Wash.	80	44 to 345	955
Sao Paulo Tramway Lt. & Pwr. Co., Sao Paulo, Brazil	29	2.3 to 66	930
Scranton Elec. Co., Scranton, Pa.	15	50 to 60	990
Southern California Edison Co., Los Angeles, Calif.	63	38 to 160	4883
St. Paul Gas Lt. Co., St. Paul, Minn.	13	2.3 to 25	160
Stone & Webster Eng. Co., Savannah, Ga.	23	22 to 88	776
City of Seattle, Seattle, Wash.	18	2.3 to 57	934
South African Gen. Elec. Co., South Africa	12	1 to 40	133
Southern California Edison Co.	16	50 to 83	1180
Syracuse Ltg. Co., Syracuse, N. Y.	16	7.5 to 160	835
Sydney Municipal Council, Australia	22	10 to 86.5	830

TABLE III (Cont'd)

CUSTOMER	NUMBER OF UNITS	KV-A. OF UNITS	TOTAL KV-A.
Tokyo Rwy. Co., Japan	99	10 to 25	1123
Tokyo Elec. Lt. Co., Japan	19	5.5 to 60	312
Texas Pwr. & Lt. Co., Dallas, Texas	15	10 to 30	280
Toronto Hydro Elec. Co., Toronto, Ontario, Canada	21	25 to 43	732
Troy Gas Co., Troy, N. Y.	12	24 to 48	456
Union Elec. Lt. & Pwr. Co., St. Louis, Mo.	64	24 to 51	1768
Union Gas & Elec. Co., Cincinnati, Ohio	25	5.75 to 57.5	1166
United Elec. Lt. & Pwr. Co., New York City	27	5.5 to 88	747
United Elec. Lt. & Water Co., Waterbury, Conn.	17	1 to 57.5	582
United Elec. Lt. Co., Springfield, Mass.	41	16.5 to 750	3007
United Gas Improvement Co., Philadelphia.	12	17.25 to 23	263
United Illuminating Co., Bridgeport, Conn.	39	7.5 to 69	1944
United Illuminating Co., New Haven, Conn.	32	2.3 to 46	1388
Utah Pwr. & Lt. Co., Salt Lake City, Utah.	30	1 to 312	3200
Utica Gas & Elec. Co., Utica, N. Y.	13	5.5 to 99	333
Union Elec. Co., Dubuque, Iowa	21	34.5 to 52	987
Washington Water Pwr. Co., Spokane, Wash.	62	1 to 60	1096
Westchester Ltg. Co., New Rochelle, N. Y.	43	1 to 103	1113
Western Elec. Co., Chicago, Ill.	14	0.2 to 10	35
Western States Gas & Elec. Co., Stockton, Calif.	16	2.3 to 120	853
Winnipeg Elec. Rwy. Co., Canada.	18	22 to 120	636
Wisconsin Trac., Lt., Ht. & Pwr. Co.	20	1 to 132	798
Wisconsin Minnesota Lt. & Pwr. Co., La Crosse, Wis.	13	2.3 to 23	278
W. K. E., Petrograd, Russia	21	1 to 25	309
Worcester Elec. Lt. Co., Worcester, Mass.	47	2.3 to 100	2120
Worcester Suburban Elec. Co., Millbury, Mass.	29	8.25 to 76	710
Yadkin River Pwr. Co.	10	20 to 375	1480

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